



**Calhoun: The NPS Institutional Archive**  
**DSpace Repository**

---

Theses and Dissertations

1. Thesis and Dissertation Collection, all items

---

1987

# A comparison of measurements from the A/E35U-3 and PWMA spectrometers.

Stewart, James T.

---

<http://hdl.handle.net/10945/22213>

---

*Downloaded from NPS Archive: Calhoun*



Calhoun is the Naval Postgraduate School's public access digital repository for research materials and institutional publications created by the NPS community. Calhoun is named for Professor of Mathematics Guy K. Calhoun, NPS's first appointed -- and published -- scholarly author.

**Dudley Knox Library / Naval Postgraduate School**  
**411 Dyer Road / 1 University Circle**  
**Monterey, California USA 93943**

<http://www.nps.edu/library>



LIBRARY  
COOPER SCHOOL  
SANTA MONICA, CALIFORNIA 93943-6002





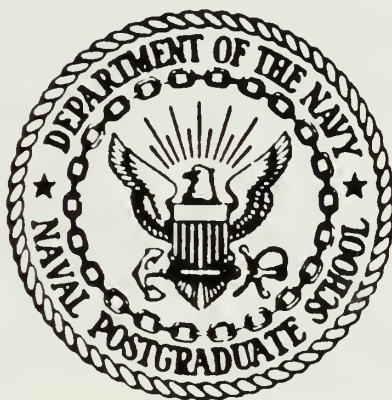






# NAVAL POSTGRADUATE SCHOOL

## Monterey, California



# THESIS

A COMPARISON  
OF MEASUREMENTS FROM THE  
A/E35U-3 AND PWMA SPECTROMETERS

by

James T. Stewart

September 1987

Thesis Advisor

H. J. Larson

Approved for public release; distribution is unlimited.

T234395





## REPORT DOCUMENTATION PAGE

1a REPORT SECURITY CLASSIFICATION UNCLASSIFIED			1b RESTRICTIVE MARKINGS		
2a SECURITY CLASSIFICATION AUTHORITY			3 DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; Distribution is unlimited.		
2b DECLASSIFICATION/DOWNGRADING SCHEDULE			5 MONITORING ORGANIZATION REPORT NUMBER(S)		
4 PERFORMING ORGANIZATION REPORT NUMBER(S)			7a NAME OF MONITORING ORGANIZATION Naval Postgraduate School		
6a NAME OF PERFORMING ORGANIZATION Naval Postgraduate School		6b OFFICE SYMBOL (if applicable) 55	7b ADDRESS (City, State, and ZIP Code) Monterey, California 93943-5000		
8a NAME OF FUNDING/SPONSORING ORGANIZATION		8b OFFICE SYMBOL (if applicable)	9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER		
8c ADDRESS (City, State, and ZIP Code) Monterey, California 93943-5000		10 SOURCE OF FUNDING NUMBERS			
		PROGRAM ELEMENT NO	PROJECT NO	TASK NO	WORK UNIT ACCESSION NO
11 TITLE (Include Security Classification) A Comparison Of Measurements From The A/E35U-3 And PWMA Spectrometers					
12 PERSONAL AUTHOR(S) STEWART, James T.					
13a TYPE OF REPORT Master's Thesis		13b TIME COVERED FROM TO		14 DATE OF REPORT (Year, Month, Day) 1987 September	
15 PAGE COUNT 77					
16 SUPPLEMENTARY NOTATION					
17 COSATI CODES			18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)		
FIELD	GROUP	SUB GROUP	JOAP, Oil Analysis Program, Spectrometry, PWMA		
19 ABSTRACT (Continue on reverse if necessary and identify by block number)					
<p>This thesis examines spectrometric oil analysis data from the A/E35U-3 and the Portable Wear Metal Analyzer (PWMA). Data from the two instruments is compared using simple linear regression analysis to obtain equations that can be used to convert the A/E35U-3 values to PWMA values. The current <i>JOAP Laboratory Manual</i> is based on A/E35U-3 measurement values and is used as an aid in determining the condition of lubricated engine components. The lack of a counterpart manual for the newly introduced PWMA makes it mandatory that values based on the A/E35U-3 have a conversion to values based on the PWMA. Through transformation equations to be developed in this paper, it will be possible for the PWMA user to utilize the current laboratory manual until a manual based on PWMA values is released.</p>					
20 DISTRIBUTION/AVAILABILITY OF ABSTRACT <input checked="" type="checkbox"/> UNCLASSIFIED/UNLIMITED <input type="checkbox"/> SAME AS RPT <input type="checkbox"/> DTIC USERS			21 ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED		
22a NAME OF RESPONSIBLE INDIVIDUAL Prof. H. J. Larson			22b TELEPHONE (Include Area Code) 408-646-2473		22c OFFICE SYMBOL 55La

Approved for public release; distribution is unlimited.

A Comparison  
Of Measurements from the  
A/E35U-3 and PWMA Spectrometers

by

James T. Stewart  
Lieutenant, United States Navy  
B.S.M.E., U. S. Naval Academy, 1981

Submitted in partial fulfillment of the  
requirements for the degree of

MASTER OF SCIENCE IN OPERATIONS RESEARCH

from the

NAVAL POSTGRADUATE SCHOOL  
September 1987

## ABSTRACT

This thesis examines spectrometric oil analysis data from the A/E35U-3 and the Portable Wear Metal Analyzer (PWMA). Data from the two instruments is compared using simple linear regression analysis to obtain equations that can be used to convert the A/E35U-3 values to PWMA values. The current *JOAP Laboratory Manual* is based on A/E35U-3 measurement values and is used as an aid in determining the condition of lubricated engine components. The lack of a counterpart manual for the newly introduced PWMA makes it mandatory that values based on the A/E35U-3 have a conversion to values based on the PWMA. Through transformation equations to be developed in this paper, it will be possible for the PWMA user to utilize the current laboratory manual until a manual based on PWMA values is released.

## TABLE OF CONTENTS

I.	INTRODUCTION .....	9
II.	OIL ANALYSIS PROGRAM .....	11
	A. BACKGROUND .....	11
	B. DISCUSSION OF INSTRUMENTS USED IN ANALYSIS .....	12
	1. A/E35U-3 .....	13
	2. PWMA .....	14
III.	DATA .....	17
	A. FIELD USE OF JOAP DATA .....	17
	B. DISCUSSION OF DATA USED .....	19
IV.	ANALYSIS .....	24
	A. OBJECTIVES .....	24
	B. SCATTERPLOTS .....	24
	C. ANALYSIS OF VARIANCE .....	31
	D. REGRESSION .....	34
	1. Regression Using All Data Points Individually (Model 1) .....	41
	2. Regression Using Sample and Level Means (Model 2) .....	44
V.	SUMMARY AND CONCLUSIONS .....	47
	APPENDIX A: GRAPHITE TUBE CODED SCATTERPLOTS .....	49
	APPENDIX B: ANOVA TABLES FOR CORRELATION DATA .....	68
	APPENDIX C: ANOVA TABLES FOR VERIFICATION DATA .....	70
	APPENDIX D: REGRESSION MODEL .....	72
	LIST OF REFERENCES .....	74
	INITIAL DISTRIBUTION LIST .....	76



## LIST OF TABLES

1. ELEMENTS MEASURED BY THE A/E35U-3 .....	13
2. ELEMENTS MEASURED BY THE PWMA .....	15
3. SAMPLE WEARMETAL EVALUATION CRITERIA AND TREND TABLE .....	20
4. DECISION MAKING GUIDANCE TABLE .....	21
5. PWMA FIELD TEST BURN SEQUENCE .....	22
6. NUMBER OF SAMPLES USED IN ANALYSIS .....	23
7. SUMMARY OF LOCATION CODED SCATTERPLOTS .....	29
8. SUMMARY OF GRAPHITE TUBE CODED SCATTERPLOTS .....	30
9. SUMMARY OF CORRELATION DATA ANOVA .....	31
10. SUMMARY OF VERIFICATION DATA ANOVA .....	32
11. SUMMARY OF VERIFICATION LEVEL ANOVAS .....	33
12. VERIFICATION LEVEL HIGHEST AND LOWEST MEANS .....	33
13. REGRESSION RESULTS FOR FE .....	35
14. REGRESSION RESULTS FOR AG .....	36
15. REGRESSION RESULTS FOR AL .....	37
16. REGRESSION RESULTS FOR CR .....	38
17. REGRESSION RESULTS FOR CU .....	39
18. REGRESSION RESULTS FOR MG .....	40
19. REGRESSION RESULTS FOR NI .....	41
20. REGRESSION RESULTS FOR SI .....	42
21. REGRESSION RESULTS FOR TI .....	43
22. RANK OF SLOPES FOR INDIVIDUAL LOCATION REGRESSIONS .....	44
23. RANK OF SLOPE STANDARD DEVIATIONS FOR LOCATIONS .....	44
24. RANK OF $R^2$ FOR LOCATION REGRESSIONS .....	44
25. REGRESSION EQUATIONS FOR MODEL 1 AND MODEL 2 .....	46
26. RECOMMENDED EQUATIONS FOR A/E35U-3 TO PWMA CONVERSIONS .....	47



27. PWMA CORRELATION DATA ANOVA TABLES .....	68
28. DASH-3 CORRELATION DATA ANOVA TABLES .....	69
29. PWMA VERIFICATION DATA ANOVA TABLES .....	70
30. DASH-3 VERIFICATION DATA ANOVA TABLES .....	71

## LIST OF FIGURES

3.1	Theoretical Concentration with Constant Fluid Replenishment .....	18
3.2	Concentration with Periodic Fluid Addition or Change' .....	18
4.1	Location Coded Scatterplot of Fe Using All Points .....	25
4.2	Location Coded Scatterplot of Ag Using All Points .....	25
4.3	Location Coded Scatterplot of Al Using All Points .....	26
4.4	Location Coded Scatterplot of Cr Using All Points .....	26
4.5	Location Coded Scatterplot of Cu Using All Points .....	27
4.6	Location Coded Scatterplot of Mg Using All Points .....	27
4.7	Location Coded Scatterplot of Ni Using All Points .....	28
4.8	Location Coded Scatterplot of Si Using All Points .....	28
4.9	Location Coded Scatterplot of Ti Using All Points .....	29
A.1	Graphite Tube Scatterplot-Location:Elmendorf-Element:Fe .....	49
A.2	Graphite Tube Scatterplot-Location:Elmendorf-Element:Ag .....	50
A.3	Graphite Tube Scatterplot-Location:Elmendorf-Element:Al .....	50
A.4	Graphite Tube Scatterplot-Location:Elmendorf-Element:Cr .....	51
A.5	Graphite Tube Scatterplot-Location:Elmendorf-Element:Cu .....	51
A.6	Graphite Tube Scatterplot-Location:Elmendorf-Element:Mg .....	52
A.7	Graphite Tube Scatterplot-Location:Elmendorf-Element:Ni .....	52
A.8	Graphite Tube Scatterplot-Location:Elmendorf-Element:Si .....	53
A.9	Graphite Tube Scatterplot-Location:Elmendorf-Element:Ti .....	53
A.10	Graphite Tube Scatterplot-Location:Langley-Element:Fe .....	54
A.11	Graphite Tube Scatterplot-Location:Langley-Element:Ag .....	54
A.12	Graphite Tube Scatterplot-Location:Langley-Element:Al .....	55
A.13	Graphite Tube Scatterplot-Location:Langley-Element:Cr .....	55
A.14	Graphite Tube Scatterplot-Location:Langley-Element:Cu .....	56
A.15	Graphite Tube Scatterplot-Location:Langley-Element:Mg .....	56
A.16	Graphite Tube Scatterplot-Location:Langley-Element:Ni .....	57
A.17	Graphite Tube Scatterplot-Location:Langley-Element:Si .....	57

A.18	Graphite Tube Scatterplot-Location:Langley-Element:Ti . . . . .	58
A.19	Graphite Tube Scatterplot-Location:Myrtle Beach-Element:Fe . . . . .	58
A.20	Graphite Tube Scatterplot-Location:Myrtle Beach-Element:Ag . . . . .	59
A.21	Graphite Tube Scatterplot-Location:Myrtle Beach-Element:Al . . . . .	59
A.22	Graphite Tube Scatterplot-Location:Myrtle Beach-Element:Cr . . . . .	60
A.23	Graphite Tube Scatterplot-Location:Myrtle Beach-Element:Cu . . . . .	60
A.24	Graphite Tube Scatterplot-Location:Myrtle Beach-Element:Mg . . . . .	61
A.25	Graphite Tube Scatterplot-Location:Myrtle Beach-Element:Ni . . . . .	61
A.26	Graphite Tube Scatterplot-Location:Myrtle Beach-Element:Si . . . . .	62
A.27	Graphite Tube Scatterplot-Location:Myrtle Beach-Element:Ti . . . . .	62
A.28	Graphite Tube Scatterplot-Location:Pensacola-Element:Fe . . . . .	63
A.29	Graphite Tube Scatterplot-Location:Pensacola-Element:Ag . . . . .	63
A.30	Graphite Tube Scatterplot-Location:Pensacola-Element:Al . . . . .	64
A.31	Graphite Tube Scatterplot-Location:Pensacola-Element:Cr . . . . .	64
A.32	Graphite Tube Scatterplot-Location:Pensacola-Element:Cu . . . . .	65
A.33	Graphite Tube Scatterplot-Location:Pensacola-Element:Mg . . . . .	65
A.34	Graphite Tube Scatterplot-Location:Pensacola-Element:Ni . . . . .	66
A.35	Graphite Tube Scatterplot-Location:Pensacola-Element:Si . . . . .	66
A.36	Graphite Tube Scatterplot-Location:Pensacola-Element:Ti . . . . .	67

## I. INTRODUCTION

Preventing failures in high performance aircraft engines and reciprocating engines due to foreseeable problems is a common sense part of the armed services mandatory safety programs. These programs call for regular maintenance to be done to decrease the opportunities for equipment failure. Through various programs it was found that some failure types can be anticipated by using spectrometers to trace wearmetal contamination levels over time in used oil samples. The actions taken based on the analysis of data resulted in savings from reduced failures and decreased maintenance on items that were not in need of scheduled periodic maintenance.

The main spectrometric device currently in use by the armed services is the A/E35U-3. It is a bulky, heavy instrument that is not easily transportable to deployment locations. A newer device, the Portable Wear Metal Analyzer, has been designed to fill the need of a 'deployable' oil analyzer. Its production model distribution is scheduled to commence in the fall of 1987. The nature of the two instruments causes them to produce differing measurements of the contaminant wearmetals in oil samples. The differences are primarily due to their differing physics and engineering design.

The measurement differences are important to those units deployed with a Portable Wear Metal Analyzer. Users of either instrument rely on the *Joint Oil Analysis Program Laboratory Manual* [Ref. 1] which is based on A/E35U-3 measurements. The oil analyst uses the manual for three primary purposes: to compare wearmetal values obtained with the wearmetal evaluation criteria and trend tables; to obtain information from the table providing decision making guidance; and to obtain supplemental information providing additional wearmetal diagnostic guidance for each type of equipment evaluated. Therefore to use the manual properly, the analyst must have the same type values as the technical manual. Through transformation equations to be produced in this paper, the Portable Wear Metal Analyzer user will be able to convert technical manual values to those that are consistent with it. As usage of the new instrument increases, the benefits of including separate wearmetal evaluation criteria and trend tables based on the Portable Wear Metal Analyzer measurements will become increasingly apparent.

An analytical development of transformation equations between the Portable Wear Metal Analyzer and the A/E35U-3 will be presented in this paper. It will be supported by a background of the oil analysis program, descriptions of the two oil analysis instruments, and a discussion of the data available. The methodology of the analysis and a description of the models used to arrive at the final conclusions of what transformation equations are required to translate technical manuals from A/E35U-3 values to Portable Wear Metal Analyzer values will be given.



## II. OIL ANALYSIS PROGRAM

### A. BACKGROUND

For several years, the Spectrometric Oil Analysis Program (SOAP) has been in use by all three military services. The Navy started a trial program in 1956 to determine if spectrometric analysis of oil samples could be used to predict engine failures. The success of the trial program led to the Navy Oil Analysis Program (NOAP). The inter-service importance of oil analysis was seen and culminated in the 1976 merger of the Army, Navy, and Air Force programs into the Joint Oil Analysis Program (JOAP).

Of many statements made on the purposes of the Joint Oil Analysis Program, Thomas Menard provides one that is simple and concise. He states that the purpose is to provide a continual monitoring of the amounts of wearmetal contaminants found in engine oil as an indicator of engine wear and possible engine failure [Ref. 2: p. 1]. The program technical manual defines the Joint Oil Analysis Program as: *The Army, Navy, Air Force, Marine Corps coordinated effort to develop a standardized, mutually beneficial program to determine equipment wear condition through the use of oil analysis* [Ref. 1: p. 1-3].

The armed services were long under a preventive maintenance program which involved set maintenance at specific intervals. Although these programs were successful, they were costly both in terms of excessive time and costs of periodically replaced maintenance items. Within the world of lubricated engines, this meant an aircraft or vehicle might unnecessarily be taken out of service for maintenance. In response to this, on-condition or reliability centered maintenance was developed. At the heart of this maintenance idea is the performance of maintenance tasks as required, vice the arbitrarily set interval schedule. The end result is increased time between maintenance actions. Senholzi [Ref. 3: p. 18] addressed the benefits of increased intervals to include reduced maintenance costs, reduced equipment downtime, and reduced safety hazards that may occur between maintenance intervals. The nature of the oil analysis program ideally suits itself to this modern approach to maintenance.

The oil analysis program uses used oil samples for testing and thereby is able to non-destructively monitor the apparent contaminant content in a lubricating system.



This is done by measuring the wearmetal concentrations of certain key elements within an oil sample. The current values of this wearmetal, and the recent trend of those values are important in ascertaining the possible condition of a system. Through the use of the applicable technical manual, high levels and problem trends may be discovered. Determination of what action is to be taken and areas to check or continue to monitor are recommended by the technical manual. Unfortunately, the oil analysis program is not a cure-all and will not discover every type of failure or guarantee to find a problem trend every time.

The oil analysis program has vastly increased over the years as economics and costly, sensitive components have played larger roles. Currently, the primary oil analysis instrument is the A/E35U-3 (hereafter called the Dash-3). It is in use worldwide by the armed services and other groups, and plays a large role in the maintenance previously described. This is demonstrated by the 1.5 million samples analyzed per year by the 100 plus Air Force JOAP laboratories alone [Ref. 4]. Due to its weight, size, and supporting peripherals required, the Dash-3 is normally used in stationary laboratories (including aircraft carriers).

In many areas, and for many engine types, the need for analysis is immediate in order to keep planes in the air and vehicles on the road. Restrictions on program usefulness are therefore evident if oil samples were required to be shipped to distant laboratories for analysis and have the corresponding delay in return of the subsequent results. The resulting requirements for a transportable oil analysis machine led to the Portable Wear Metal Analyzer (hereafter called the PWMA). It is a lightweight instrument that is easily transported utilizing two small cases. Its design makes it ideal for units that are deployed away from a nearby JOAP laboratory and which still need quick, reliable results. In the following sections, the principles of operation of both instruments will be discussed.

## **B. DISCUSSION OF INSTRUMENTS USED IN ANALYSIS**

The measurements of two different types of spectrometers are compared in this analysis. The difference in their measurements is rooted in the different physical principals they employ, atomic emission and atomic absorption spectrometry. The following is provided as background for the physical concepts and uses of these two instruments.

## 1. A/E35U-3

The A/E35U-3 (Dash-3) fluid analysis spectrometer is the standard instrument for the Joint Oil Analysis Program today. It is an atomic emission spectrometer and is manufactured by the Baird Corporation of Bedford, Massachusetts. It is a self-contained unit that weighs 800 pounds and has dimensions of 60 x 52.5 x 49.5 inches. Within its shipping container, it weighs 1400 pounds and has dimensions of 74 x 67 x 47.75 inches [Ref. 1: p.4-2]. The instrument has the capability of measuring twenty elements within an oil sample. These twenty elements are listed in Table 1. The measurement of all elements is accomplished simultaneously.

TABLE 1  
ELEMENTS MEASURED BY THE A/E35U-3

Fe	Iron	Na	Sodium	Ba	Barium
Ag	Silver	Ni	Nickel	Cd	Cadmium
Al	Aluminum	Pb	Lead	Mn	Manganese
Be	Beryllium	Si	Silicon	Mo	Molybdenum
Cr	Chromium	Sn	Tin	V	Vanadium
Cu	Copper	Ti	Titanium	Zn	Zinc
Mg	Magnesium	B	Boron		

Atomic emission spectrometers are optical type instruments used to determine the concentration of wear metals in lubricating fluid. The analysis is accomplished by subjecting ("burning") the sample to a high voltage spark which energizes the atomic structure of the metallic elements, causing the emission of light. Within the Dash-3, this is done through the use of a rotating disk electrode spark source. The light is caused by the atomic structures of the elements being excited into higher energy states by the high temperature and then returning to their ground state through the emission of light. One or more characteristic wavelengths may be given off by each element. The emitted light is subsequently focused into the optical path of the spectrometer and separated according to wavelength, converted to electrical energy and then measured. The emitted light for any element is proportional to the concentration of wear metal suspended in the lubricating fluid. This makes possible the estimates for the wear metal concentration levels for each element that are normally measured in parts per million (ppm). [Ref. 1,5: pp. 2-1, 21]

The final values obtained from a spectrometer are subject to many sources of error. Several of these sources apply to both the Dash-3 and the PWMA. Some of the reasons for error and factors that may influence the actual value obtained are given below [Ref. 1: pp. 2-3,2-4]:

- *Oil sample from wrong component*
- *Contaminating substances in system*
- *Oil is not homogeneous in content*
- *Type of instrument being used, emission or absorption spectrometer*
- *Contaminated/poor quality calibration standards*
- *Changes of rod or disc electrodes without restandardizing equipment*
- *Metallic components in fluid additives within oil manufacture*
- *Electrolytic corrosion due to seasons, storage*
- *Dirt and sand contamination*
- *Metal content of the fuel*
- *Break-in period of new or recently overhauled components*

Another possible problem source is that of using synthetic ester oil to calibrate the instrument. Rhine [Ref. 6: p. 39] found this to directly effect the Dash-3 *by the enhancement of emission from metals in an ester oil matrix relative to metals in a hydrocarbon matrix*. The end product of this is superficially high readings from the ester oil when calibration is done with a hydrocarbon oil. Similarly, problems are introduced by calibrating an instrument using standards prepared in a synthetic oil matrix. Specific to the Dash-3 design, errors may be introduced if there are inefficiencies in the particle transport capability of the rotating disk electrode, or in the vaporization and excitation of those transported particles at the arc/spark source [Ref. 6: p. 53]. A study for the Air Force by United Technologies Corporation placed some of the precision problems of the Dash-3 on *the variable excitation characteristics of direct current (dc) arcs operated in air, inaccuracies due to variations in sample viscosity*, and the inability to analyze particles larger than 10 micrometers in size [Ref. 7: p.1].

## 2. PWMA

The Portable Wear Metal Analyzer (PWMA) is planned as the standard instrument for deployments to remote areas where the Dash-3 is not located or suitable. It is a graphite furnace atomic absorption spectrometer manufactured by the Perkin-Elmer Corporation's Applied Science Division of Pomona, California. It is composed of two self-contained units that double as shipping containers. The units are lightweight, weighing 60 pounds and 40 pounds respectively, and have identical dimensions of 11 x 18 x 18 inches [Ref. 8: p. 1-4]. The instrument has the capability of measuring nine elements within an oil sample, these elements are listed in Table 2 .



The measurements of all elements is accomplished simultaneously. The instrument has repeatability specifications of +/- 1ppm or +/- 2.5% of full scale, whichever is greater.

TABLE 2  
ELEMENTS MEASURED BY THE PWMA

Fe Iron	Cr Chromium	Ni Nickel
Ag Silver	Cu Copper	Si Silicon
Al Aluminum	Mg Magnesium	Ti Titanium

Atomic absorption spectrometers are similar to their emission counterparts in being optical type instruments used to determine the concentration of wear metals in a lubricating fluid. However, the physical concepts of the machines are very different. With the atomic absorption spectrometer, the atomic structures of the elements present become energized enough by high temperatures to absorb light (rather than emit light as in the Dash-3). Within the PWMA, the heating is done in a graphite furnace tube whereas other atomic absorption spectrometers usually use a flame. The graphite furnace atomic absorption spectrometer uses the graphite tube as a resistive heating element to atomize the wear metals. Light energy having the same ("characteristic") wavelength of the element being analyzed is then radiated through the graphite tube. Two multi-element hollow-cathode lamps are used for this in the PWMA. The resultant light is converted to electrical energy and measured electronically by using photomultiplier detectors. The amount of light energy absorbed by the elements in the optical path of the graphite tube is proportional to the concentration of wear metal suspended in the lubricating fluid. This makes possible the estimates for the wear metal concentration levels for each element that are normally measured in parts per million. The after to before ratio of light intensities that is used makes the signal less susceptible to intensity variations of the spectra caused by the environment. [Ref. 1,4: pp 2-2,6]

Six prototype PWMA instruments were acquired by the Air Force *for testing in an operational environment with military personnel as operators* [Ref. 9: p. 2]. Field test plans were developed by the Air Force Wright Aeronautical Laboratories (AFWAL). As part of this plan, instruments were provided to four locations to be used alongside the Dash-3. Locations in receipt of these instruments were: Naval Air Rework Facility (NARF), Pensacola; Elmendorf AFB; Langley AFB; and Myrtle Beach AFB. Preliminary testing on a prototype PWMA showed it to be successful in

measuring particles up to 20 micrometers in size [Ref. 4: p. 60]. The prototype PWMA's currently use preprogrammed algorithms in calibrating themselves. This is done using three successive calibration runs. The runs specify three points for each element's calibration curve algorithm and may result in small inaccuracies. Further areas of possible error are described in Reference 4 .

Initial testing of the PWMA has shown it to yield values that are approximately one-half of those obtained with the Dash-3. For example, a sample that measures 11 ppm on the Dash-3 may only measure 6 ppm on the PWMA. The wearmetal concentration level (in ppm) is readily seen from this to depend on which instrument is used. Investigation of this point shows the controlling factor to be in whether the measurement is based on atomic emission (as with the Dash-3), or based on atomic absorption (as with the PWMA). This difference in using light emission or light absorption for estimating an element concentration level leads to the separate scales obtained.

### III. DATA

#### A. FIELD USE OF JOAP DATA

Once values have been obtained from an oil analysis spectrometer, an analyst must be able to do more than add them to a database. His primary goal is to determine if there is any abnormal condition present or developing in the parent component of the sample. This goal may be achieved by following the wearmetal methodology presented by the *JOAP Laboratory Manual*. The major parts of the method are [Ref. 1: p.6-1]:

- *a wearmetal evaluation and trend table*
- *a table providing decision making guidance*
- *supplemental information providing additional wearmetal diagnostic guidance for each type of equipment evaluated*

When consumption and replenishment of fluid is continuously balanced in a component, the wearmetal concentration within the lubricant tends to increase after a fluid change until a steady state level is achieved. This effect is shown in Figure 3.1 . The wearmetal concentration steady state point in this model is thus a function of two variables: rate of fluid consumption and replenishment; and the rate of wearmetal production by internal friction within the equipment. When the fluid is added or changed periodically, as is done with many items of equipment, a sawtooth pattern emerges. Such a pattern is shown in Figure 3.2 . [Ref. 1: pp. 2-5,6]

Because of a tendency toward a steady state level, it is not only important to know the actual wearmetal concentration, but also to know the rate of increase (trend) of that concentration. Increased sampling is always recommended as levels increase in order to decrease the probability of a wearmetal concentration going from normal to abnormal without an intermediate sample. The exact procedure the oil analysts are trained to follow in evaluating a sample is a logical sequence of actions. The JOAP manual mandates the following procedure [Ref. 1: p. 6-2]:

- *Analyze the sample and obtain the wearmetal concentration results.*
- *Determine the range where each critical wearmetal falls from the appropriate wearmetal evaluation criteria and trend table.*
- *Compare the wearmetal concentration ranges of the current sample with the ranges of the last previous sample.*
- *Determine the wearmetal trend (trend value for a ten hour period).*



- If a maintenance action is indicated, consult the supplemental information provided.

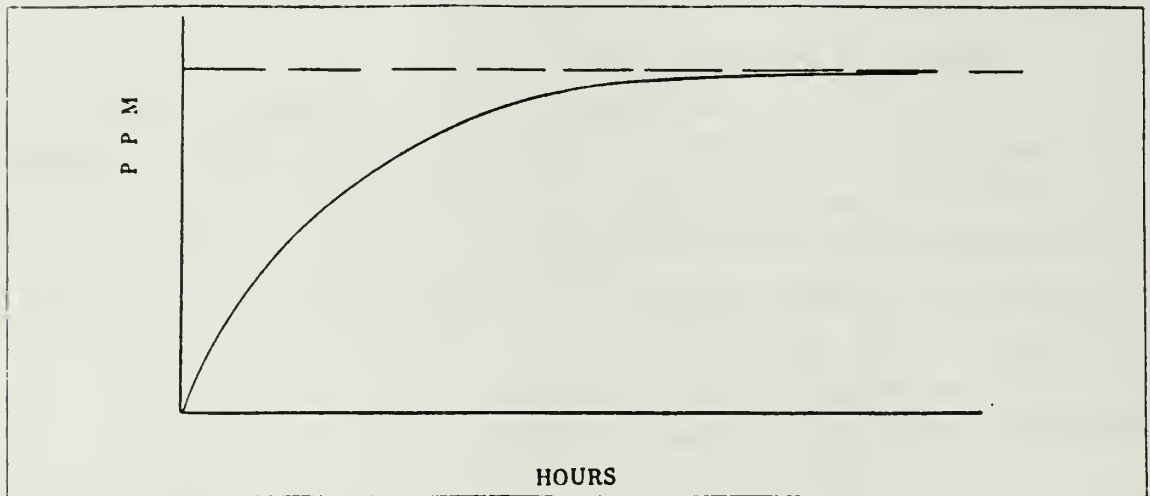


Figure 3.1 Theoretical Concentration with Constant Fluid Replenishment.

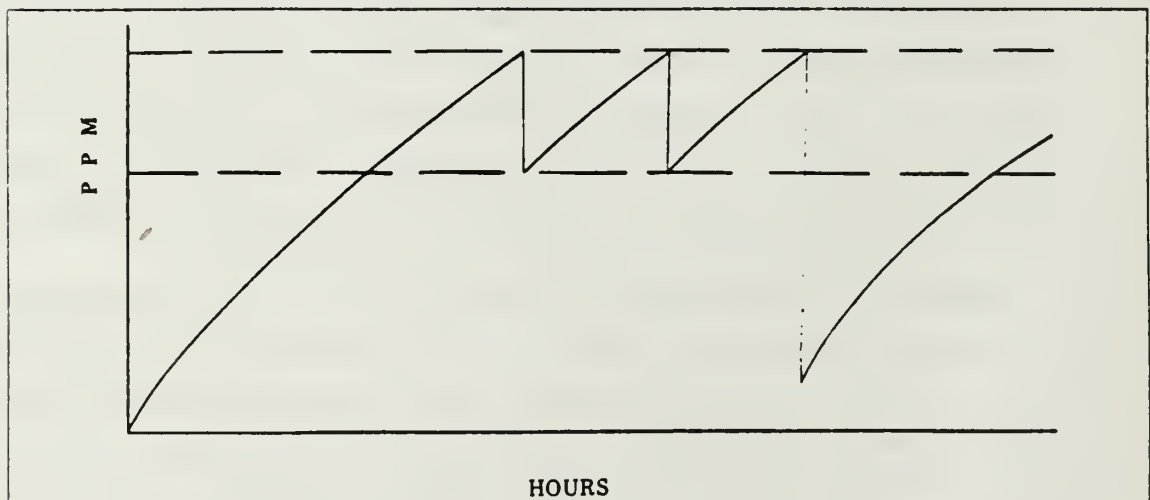


Figure 3.2 Concentration with Periodic Fluid Addition or Change.

Table 3 [Ref. 1: pp. 98,99] is provided to gain a fuller understanding of the oil analysts' procedure. It provides the wearmetal evaluation criteria and trend table for the T64 series engine commonly used in the CH-53A,D helicopter. A sample scenario would show the analyst checking for a normal trend by comparing the current values with those of the previous sample, and then checking for to see if the current values are

in a normal range. With that information he would enter a decision making guidance table and obtain from it the advice codes it lists. This decision aid is shown in Table 4. When the code indicates anything abnormal, some type of action is recommended. Normally the initial action is to request a 'red-tagged' sample and to cease operation of the equipment. The 'red-tagged' sample is to gain confirmation of the abnormal results before any type of maintenance action will be recommended. If abnormal results are confirmed, the supplemental information provided in the technical manual is consulted and a maintenance action is recommended. The supplemental information may be very useful in pin-pointing possible problem areas and identifying a specific recommendation to the sample originator [Ref. 1: p. 6-1].

An example of the above procedure using the tables shown is given here. An oil analyst receives a sample from an engine that was previously sampled twenty engine hours earlier. His logbook shows that its last sample was normal and had values as follows (in ppm): Fe-10, Ag-0, Al-2, Cr-0, Cu-1, and Mg-1. The present sample is tested with the following results: Fe-19, Ag-4, Al-6, Cr-0, Cu-1, and Mg-1. The analyst determines the ten-hour trend values to be (in ppm/hour): Fe-4.5, Ag-2, Al-2, and the remainder zero. Using Table 3, he would discover Fe and Ag to have abnormal trends and high ranges, with all other elements normal. Entering Table 4 in the high range in column one and reading across through the normal range in column two for the previous sample, and then through the abnormal trend in column three, one obtains the advice code P from column four. The analyst translates this code as: *do not fly/operate; do not change oil; submit sample ASAP* and relays this to the sample originator. The 'red-tagged' sample is subsequently analyzed for verification of the last results. If results are identical to the previous ones, the appropriate advice code from column five is utilized. This might include using the lower part of Table 3 to determine possible maintenance problems such as the power turbine shafts.

## **B. DISCUSSION OF DATA USED**

The data in this analysis was obtained from a field test for the evaluation of the Portable Wear Metal Analyzer that was conducted in 1985. The data was collected over a two month period from four locations: NARF, Pensacola, Elmendorf AFB, Langley AFB, and Myrtle Beach AFB. Both Dash-3's and prototype PWMA's were in the laboratories at each site in order to provide data for their comparisons. Only the nine elements that the PWMA is able to measure were recorded for the Dash-3. Though the primary objective of the field test was to determine the functionality of the PWMA [Ref. 10: p.1], the data obtained easily lent itself to this study.

TABLE 3  
SAMPLE WEARMETAL EVALUATION CRITERIA AND TREND TABLE

ENGINE: T64-6/-7/-7A/-10/-12/-413/-415  
AIRCRAFT: (CH-53A/D) (RH-53A/D) (VH-53D) (UC-8A)

A/F35U-3

	Fe	Ag	Al	Cr	Cu	Mg		
Abnormal Trend (PPM Increase in 10 hrs)	4	2	4	2	3	2		
Normal Range	0-14	0-2	0-10	0-2	0-6	0-5		
Marginal Range	15-17	N/A	11-12	3	7	6		
High Range	18-21	3	13-14	4	8-9	7		
Abnormal	22+	4+	15+	5+	10+	8+		

Average Concentration Other Elements:

Ni=1

Pb=2

Si=3

Sn=7

Ti=1

Mo=1

ENGINE: T64-6/-7/-7A/-12/-413/-415 (Cont)  
AIRCRAFT: (CH-53A/D) (RH-53A/D) (VH-53D)

Fe

Main bearing balls, rollers and races, accessory gearbox gears and shafts, PTO gears

Fe Ag

Accessory gearbox bearings

Fe Ag

Power turbine shafts

Fe Ag Cu

PTO bearings

Ag Cu

Main bearing cages

Al

Lube and scavenge oil pumps and thermal gradient housing

#### NOTE

Thermal gradient housing could be prime source of Al especially after heavy use of engine anti-icing system.

TABLE 4  
DECISION MAKING GUIDANCE TABLE

DECISION MAKING GUIDANCE

RANGE, THIS SAMPLE	RANGE, PREVIOUS SAMPLE	TREND	RECOMMENDATION CODE	
			CATEGORY I	CATEGORY II
NORMAL	Normal	Normal	A	N/A
		Abnormal	A, B or C	N/A
	Marginal	N/A	A or B	N/A
	High	N/A	A or B	N/A
	Abnormal	N/A	A or B	N/A
	Normal	Normal	A or B	N/A
		Abnormal	B	C
	Marginal	Normal	A	N/A
MARGINAL		Abnormal	B	C
	High	N/A	A or B	N/A
		N/A	A or B	N/A
	Abnormal	N/A	A or B	N/A
	Normal	Normal	B	C
		Abnormal	P	F, H, J, S, T, U
	Marginal	Normal	C	N/A
		Abnormal	P	F, H, J, S, T, U
HIGH		Normal	C	N/A
	High	Abnormal	P	F, H, J, S, T, U
		N/A	C or B	N/A
	Abnormal	N/A		
	Normal	Normal	P	C, J
		Abnormal	P	F, H, J, S, T, U
	Marginal	Normal	C	N/A
		Abnormal	P	F, H, S, T, U
ABNORMAL		Normal	C E	N/A
	High	Abnormal	P	F, H, S, T, U
		Normal	P or F	E, H, S, T, U
	Abnormal	Abnormal	T, S or U	N/A

As designed, the test called for each site to use six graphite tubes for 160 sample 'burns' each. Many samples were to be tested five consecutive times when analyzed. The test plan was designed for repetitive four day cycles. The sequence of events it followed for the PWMA is shown in Table 5 [Ref. 10: p. 11]. The sequence of events for the Dash-3 was nearly identical to that of the PWMA. Consistency in following this test plan varied among the different locations. This directly affected the number of sample results provided by each location. A compilation of the number of samples used in this analysis from each location is given in Table 6 .

TABLE 5  
PWMA FIELD TEST BURN SEQUENCE

Day 1	Calibration Runs Verification Samples Correlation Samples 1, 2, 3 Random Samples Verification Samples
Day 2	Reslope Verification Samples Correlation Samples 4,5 Random Samples Calibration Check Samples Random Samples Verification Samples
Day 3	Calibration Samples Verification Samples Correlation Samples 6,7 Random Samples Verification Samples
Day 4	Reslope Verification Samples Correlation Samples 8,9 Random Samples Calibration Check Samples

As noted in Table 5, there were four main classes of samples tested with the instruments: calibration, verification, correlation, and random samples. Calibration samples of MIL-L-7808 oil were used for the internal calibration of the PWMA. Three calibration samples containing 20%, 50%, and 100% respectively of full scale values for all nine metals were used for the calibration runs and were also used for quality assurance in the calibration check runs. Verification samples were made in MIL-L-7808 oil and contain concentration levels of 10%, 40%, and 70% of the top of the



TABLE 6  
NUMBER OF SAMPLES USED IN ANALYSIS

	Elm	Lan	Myr	Pen
Correlation Samples	53	26	24	80
Verification Samples	65	33	27	39
Total Samples	118	59	51	119

dynamic range. Correlation samples were designed to reflect the pseudo-realism of having various concentration levels for each element. Nine different correlation samples were used in the test. Because of the inavailability of MIL-L-7808 oil with significant wearmetal levels for the correlation samples, used MIL-L-23699 turbine engine oil was utilized after blending with organo-metallic concentrates as necessary by JOAP-TSC. These samples were ensured to contain a minimum of seven wearmetals. The random samples were routine daily samples obtained at each site and were typically MIL-L-7808 lubricants from the Air Force, and MIL-L-23699 lubricants from the Navy. Reslopes were calibration checks using a 50% of full scale calibration sample. [Ref. 10: p. 6]

Due to the nature of the calibration runs and the low values in the random samples, only verification and correlation samples were used in this analysis. This made possible a total of twelve samples, consisting of three different verification and nine different correlation samples. Sample numbers (or levels as appropriate) were kept in the database as well as the graphite tube number in which a sample was used for later use in determining their means. Each sample 'burn' with the PWMA correlation samples was repeated five consecutive times. In order to provide a one to one correspondence of data between the instruments, the average of the consecutive 'burns' was used in the analysis. The PWMA value (average value for correlation samples or actual measurement for verification samples as appropriate) was coupled with its counterpart on the Dash-3 that was closest in time. In normal cases this led to results such as pairing the first verification sample 'level 10' measured during the day from each instrument. Differences in sample sizes for the various element-location combinations was a result of missing data points and the removal of extreme outliers from the data.



## IV. ANALYSIS

### A. OBJECTIVES

The objective of this analysis is to find a functional relationship between Dash-3 and PWMA measurements for the nine elements that the PWMA measures. Analysis of variance techniques will be used in order to determine what effects cause significant differences in the measurements obtained. Regression analysis will be used to yield the parameters of an equation to relate the instrument measurements, and to obtain the standard deviations of those parameters. The coefficient of determination or  $r^2$  statistic will be used as a measure of how well the model fits the data and to compare the different models. It is also known as the square of the coefficient of determination and represents the percentage of total variation explained by the model.

### B. SCATTERPLOTS

Scatterplots of the data are useful in determining areas for further investigation. They were used in this analysis to provide insight into the rejection of the hypothesis that there is no difference in measurements due to location. The rejections are described in the analysis of variance section. The scatterplots in Figures 4.1 - 4.9 are location coded and include all verification and correlation sample data points. As reflected in Table 7, examination of these plots show Pensacola with higher values and Elmendorf with lower values for most elements (seven of nine in each case). The consistent extremes shown by these two locations are a primary reason for differences found between locations. The number of samples submitted does not explain the extremes as both had larger sample sizes. Coded scatterplots of the graphite tube furnaces for each location/element combination are shown in Appendix A. The tubes were reviewed in particular because they were prototypes and not production models. The quality controls that will be used in manufacturing the production models was not used for the prototypes, consequently, it was suspected that they could be a large source of variability in the measurements. The graphite furnace tubes were provided to each site with the tubes labeled sequentially within sites. Some tubes malfunctioned and could not be used due to calibration failures, causing skips in the tube numbers reported. Most tubes did not last as long as expected originally so all tubes did not have an equal number of burns. With minor exceptions, no unusual characteristics

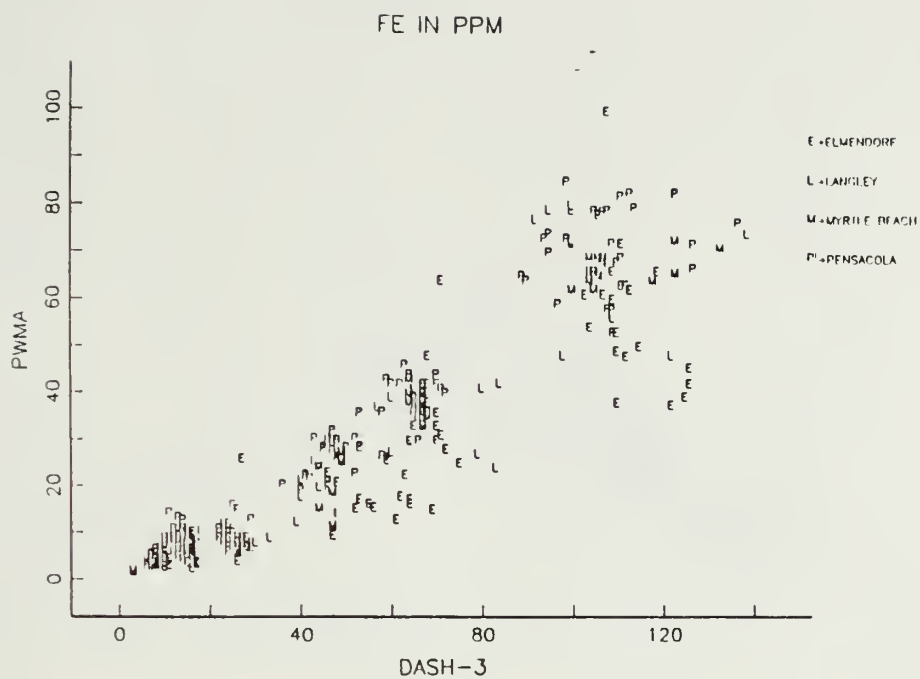


Figure 4.1 Location Coded Scatterplot of Fe Using All Points.

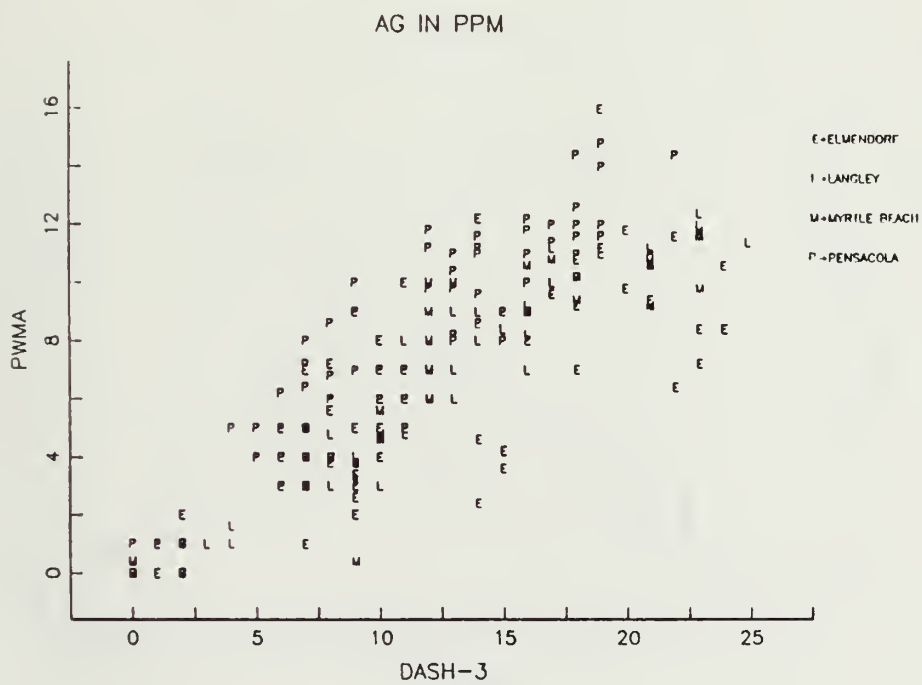


Figure 4.2 Location Coded Scatterplot of Ag Using All Points.

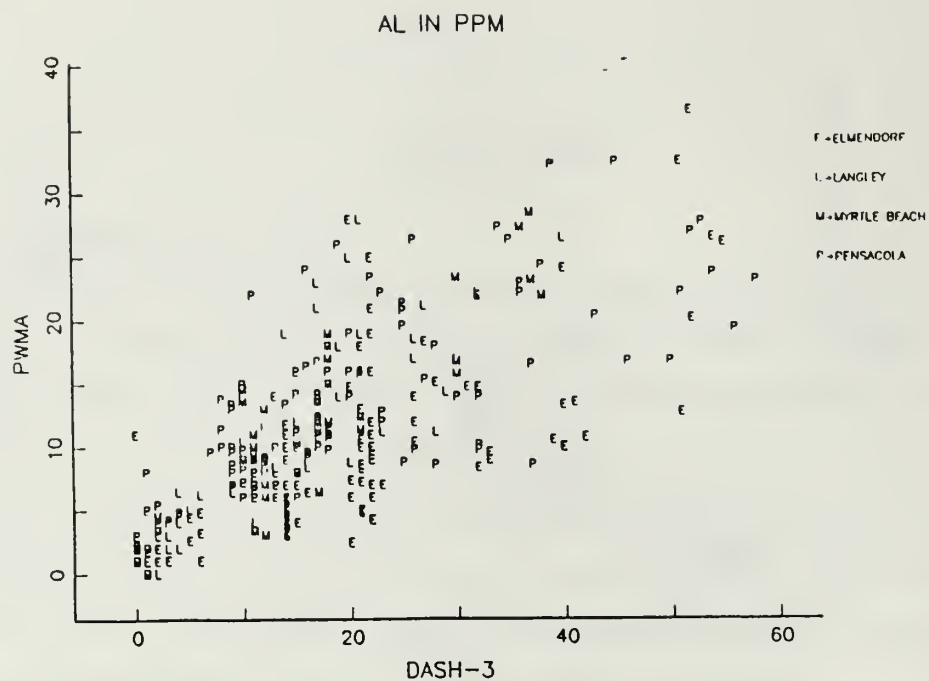


Figure 4.3 Location Coded Scatterplot of Al Using All Points.

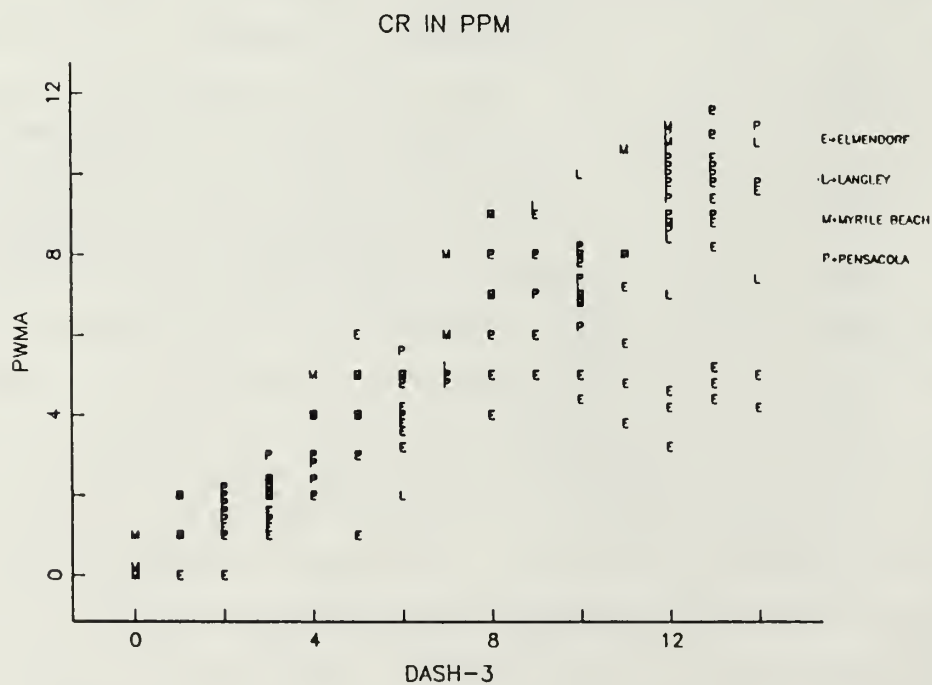


Figure 4.4 Location Coded Scatterplot of Cr Using All Points.

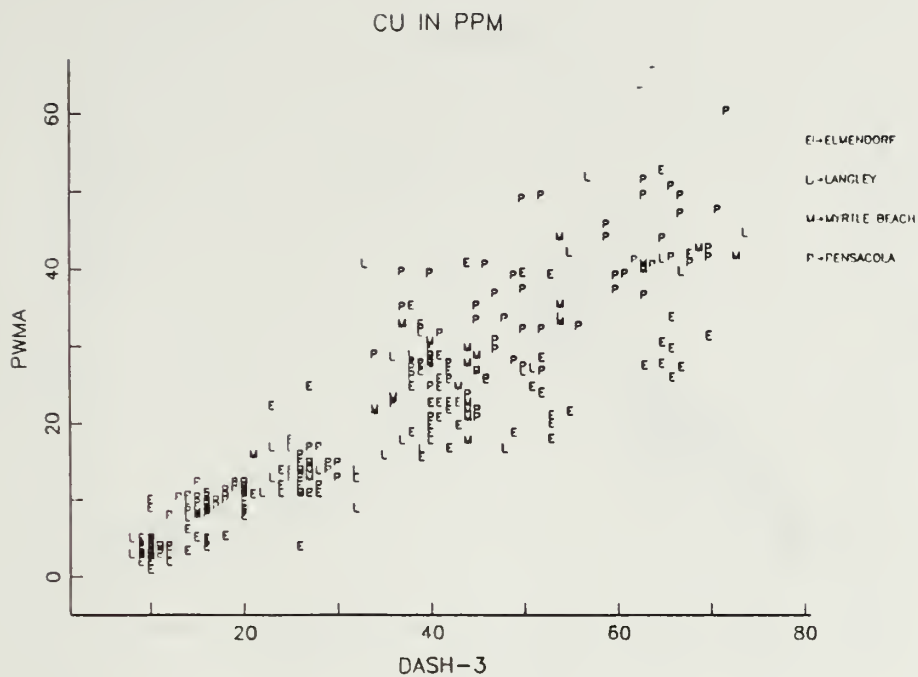


Figure 4.5 Location Coded Scatterplot of Cu Using All Points.

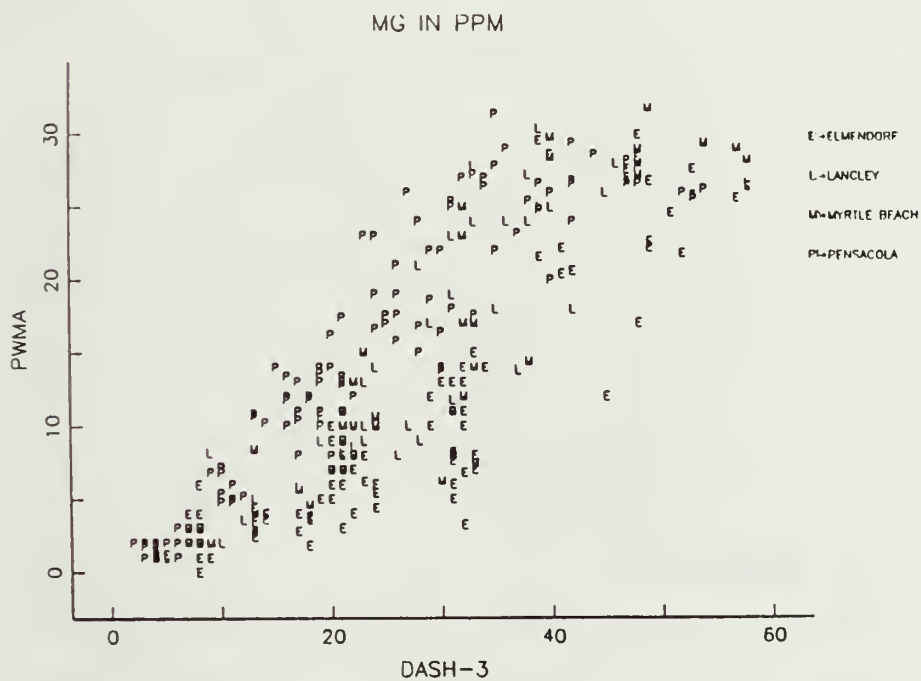


Figure 4.6 Location Coded Scatterplot of Mg Using All Points.

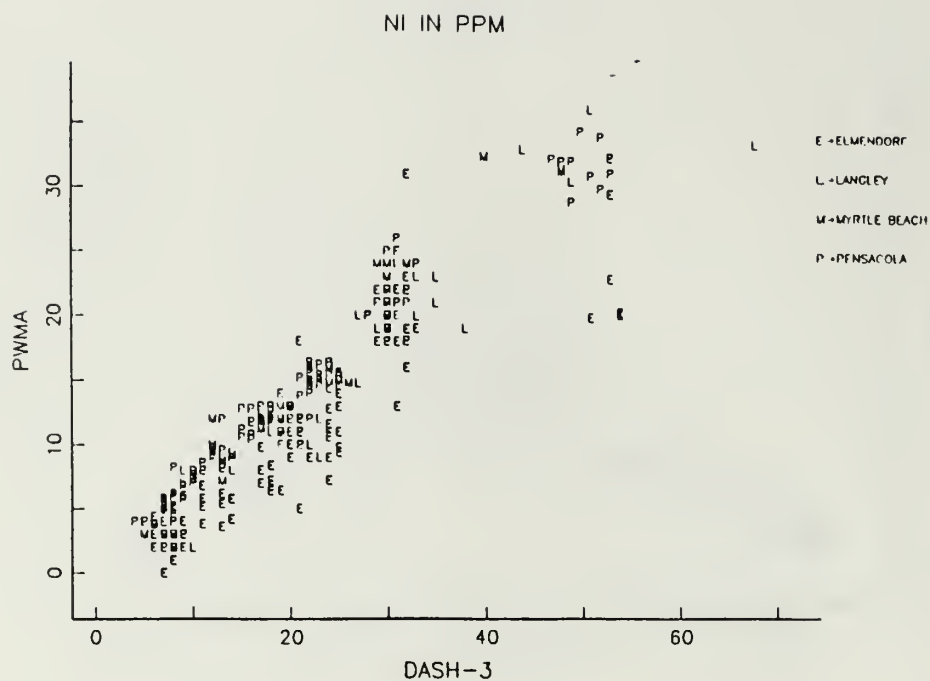


Figure 4.7 Location Coded Scatterplot of Ni Using All Points.

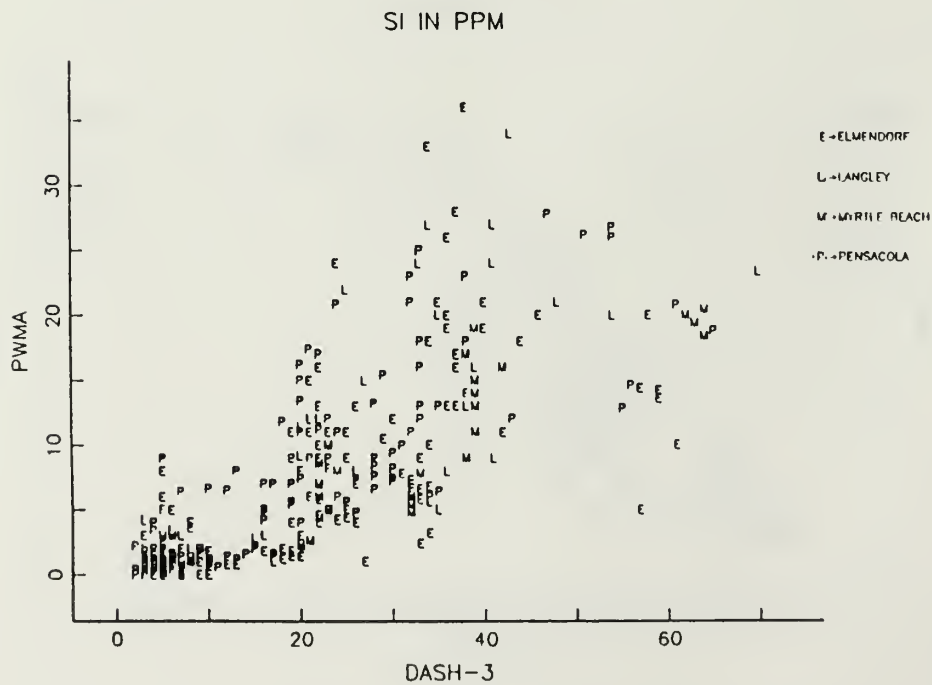


Figure 4.8 Location Coded Scatterplot of Si Using All Points.



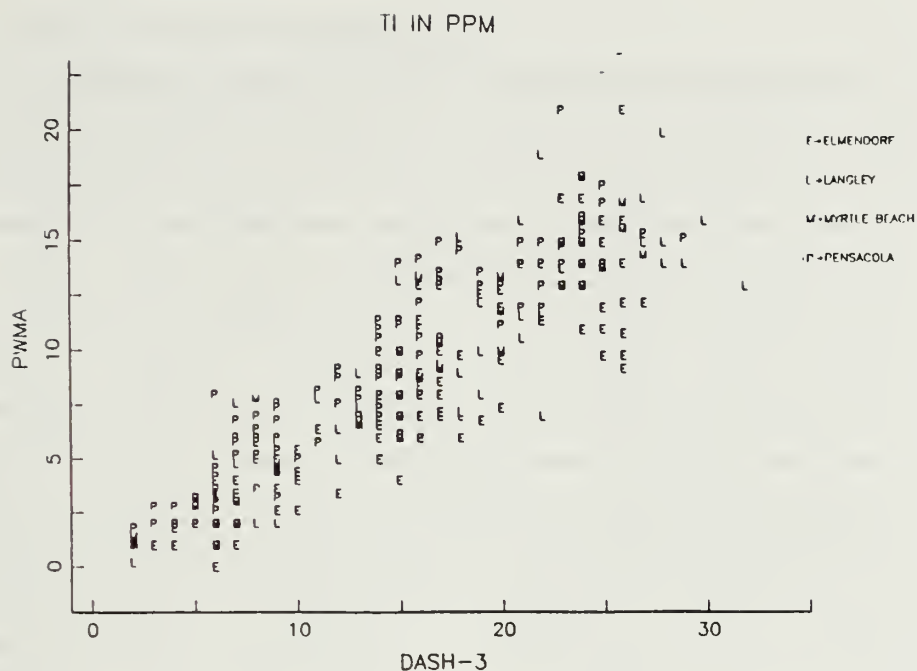


Figure 4.9 Location Coded Scatterplot of Ti Using All Points.

TABLE 7  
SUMMARY OF LOCATION CODED SCATTERPLOTS

Element	Location Coded Results	
Fe	P high	E low
Ag	P high	E low
Al		
Cr		E low
Cu	P high	E low
Mg	P high	E low
Ni	P high	E low
Si	P high	
Ti	P high	E low

were found. A summary of the graphite furnace tubes in Table 8 shows Elmendorf used six different graphite tubes in its experiments with tube 1 measuring higher than normal in seven elements, tube 7 high in five elements, and three points of tube 5 high in seven elements (indicated by  $S_3$ ). Though the three points from tube 5 appeared to be an aberration, they were included in the analysis. Higher/lower than normal is not

TABLE 8  
SUMMARY OF GRAPHITE TUBE CODED SCATTERPLOTS

	Elm	Lan	Myr	Pen
Fe	1,5 <sub>3</sub> ,7 Hi	5 Hi 7 Lo		1 Hi
Ag	1,5 <sub>3</sub> Hi		3 Lo	16 Hi
Al	1 Hi			
Cr	1,5 <sub>3</sub> Hi	1 Hi		1 Hi
Cu	1,5 <sub>3</sub> Hi	3 Hi 7 Lo		
Mg	7 Hi	7 Lo		
Ni	1,5 <sub>3</sub> ,7 Hi			
Si	5 <sub>3</sub> ,7 Hi			
Ti	1,5 <sub>3</sub> ,7 Hi	2 Lo		1 Lo
Tubes Used	1,2,3,4 5,7	1,2,3,5 7	1,2,3,4 5,6	1,3,4,5 6,8,9,12 13,15,16

used in a statistical sense but as a subjective term. A symbol that characteristically plotted as a maximum/minimum value across the range of x values was given the appropriate subjective term. The five tubes used by Langley showed tube 7 measuring low in three elements, tube 2 low in one, and tubes 1, 3, and 5 high in one element apiece. Myrtle Beach used six tubes and showed nothing unusual except for tube 3 measuring low in one element. Pensacola provided the most data and used the most tubes, 11. Its scatterplots are not unusual except for tube 1 being high for two elements and low for one, and tube 16 being high for one element. In summary, the scatterplots indicate that the locations provide different measurements, with Pensacola normally high, and Elmendorf normally low. The graphite furnace tubes do appear to have a statistically significant difference within each instrument, but not a practical difference.

### C. ANALYSIS OF VARIANCE

As stated, a superior tool to scatterplots in determining if various effects are statistically significant is analysis of variance. It is used here to determine if the various instruments (the four prototype PWMA's and the four Dash-3's) are providing measurements close enough to be considered not statistically different. Examples of the various ANOVA models applicable can be found in References 11 and 12 . Using the standard assumptions of normality, an alpha level of significance of 0.05 is used throughout this paper. Statistical significance obtained may be more restrictive in its determinations than what would be considered a practical significance by the oil analysts. In other words, the numbers may be close enough to be considered the same by the analysts. No assertions as to what this practical significance might be will be addressed. Analyses of variance were run on the correlation samples to determine if location, sample, or their interaction is significant. The resulting tables and associated p-values are given in Appendix B. As summarized in Table 9, location differences were found with all elements except Ni on the Dash-3. Location-sample interactions were significant with four elements for the Dash-3, and in all but two elements for the PWMA. These results imply greater variability in the prototype PWMA instruments.

TABLE 9  
SUMMARY OF CORRELATION DATA ANOVA

	PWMA			Dash-3		
	LOC	SAM	INT	LOC	SAM	INT
Fe	X	X	X	X	X	X
Ag	X	X	X	X	X	
Al	X	X	X	X	X	
Cr	X	X	X	X	X	
Cu	X	X		X	X	X
Mg	X	X	X	X	X	
Ni	X	X			X	X
Si	X	X	X	X	X	
Ti	X	X	X	X	X	X

X denotes statistically significant at  $\alpha = .05$

The analyses of variance on the verification sample data for both instruments is provided with their corresponding p-values in Appendix C, and a summary given in Table 10 . Table 10 shows that when interactions were considered, location was not

significant for three PWMA elements (Cu, Si, and Ti) and one Dash-3 element (Ni). Analysis of interactions showed all PWMA elements except Mg did not have significant interactions, while all Dash-3 elements but Ni did have a significant interaction. In contrast to the correlation data, this shows a strong variability in the

TABLE 10  
SUMMARY OF VERIFICATION DATA ANOVA

	PWMA				Dash-3		
	LOC	LEV	INT		LOC	LEV	INT
Fe	X	X			X	X	X
Ag	X	X			X	X	X
Al	X	X			X	X	X
Cr	X	X			X	X	X
Cu		X			X	X	X
Mg	X	X	X		X	X	X
Ni	X	X				X	
Si		X			X	X	X
Ti		X			X	X	X

X denotes statistically significant at  $\alpha = .05$

Dash-3 compared to the prototype PWMA. As expected and designed, the different verification levels and different correlation samples were significantly different within their respective groups. Further analysis on the verification data is summarized in Table 11 , which takes a closer view of location effects at each of the three levels. Recall that these levels represent the samples which contain 10, 40, and 70 percent of the full scale dynamic range for each element. The table gives each instrument's corresponding element-level matrix of significant location effects. The matrix shows the prototype PWMA to be very consistent in its measurements across locations as opposed to the Dash-3, which lacks consistency for most elements and levels. The basis for this statement lies in the few holes shown in the Dash-3 matrix and the few marks in the PWMA matrix. Examination of location effects on the verification data was also done using means. The highest and lowest location mean was recorded for each element and is shown in Table 12 . From this it can be seen that a location that is high(low) for an element is usually high(low) for all three levels for that element. Of interest is that the location that measures high(low) for an element on one instrument will not normally be high(low) on the other instrument as well. This shows an

TABLE 11  
SUMMARY OF VERIFICATION LEVEL ANOVAS

	PWMA				Dash-3		
	10	40	70		10	40	70
Fe			X		X	X	X
Ag					X	X	X
Al		X			X	X	X
Cr	X		X		X	X	X
Cu							X
Mg		X	X			X	X
Ni							
Si					X	X	X
Ti					X	X	

X denotes statistically significant at  $\alpha = .05$

apparent low correlation between the two instruments regarding the same location being high(low) for a particular element.

TABLE 12  
VERIFICATION LEVEL HIGHEST AND LOWEST MEANS

	PWMA				Dash-3		
	10	40	70		10	40	70
Fe <sup>Hi</sup> Lo	P M	P E	L E		M P	L P	E P
Ag <sup>Hi</sup> Lo		M L	M P		L P	L P	L P
Al <sup>Hi</sup> Lo	P E	M E	L E		L P	E P	E P
Cr <sup>Hi</sup> Lo		M E	L E		P M	L M	L M
Cu <sup>Hi</sup> Lo	P E	P E	P E			P M	L M
Mg <sup>Hi</sup> Lo	L P	L P	L P		P E	P E	L E
Ni <sup>Hi</sup> Lo		P M	L M				M L
Si <sup>Hi</sup> Lo	E P	E P	L P			E M	L M
Ti <sup>Hi</sup> Lo	M P	L P	L P			L P	L P



## D. REGRESSION

Regression is used as the principal tool to determine functional relationships (transformation equations) between the measurements of the two different instruments. Tables 13 - 21 show for each element the results of several regressions run on the data. For each regression, the following are given:  $r^2$ , the intercept and its standard deviation, the slope and its standard deviation, and the number of data points used in the regression. Two principal models were analyzed, the first model used all data points from all locations regardless of the location sample sizes (model 1); and the second model used the means of the samples and levels at each location, thereby allowing equal sample sizes (model 2). The various sample sizes were presented in Table 6 . Appendix D gives a basic regression model. The majority of regressions done used the simple linear model of:

$$PWMA = B_0 + B_1(DASH-3) + e . \quad (\text{eqn 4.1})$$

Other regressions used a quadratic fit or used simple linear fits on transformations of the data. No attempts were made to force the resulting equations through the origin.

An ideal regression using the simple linear model with least squares estimators has a high  $r^2$  . It will also meet the assumption of constant variance across the range of interest (homoscedascity), and that of normalized residuals. The usual least squares regression estimators have optimal properties if one assumes that the variance of the y values remains constant as x increases, together with

$$E[y_i] = a + bx_i . \quad (\text{eqn 4.2})$$

Many measuring instruments have variances which increase with the magnitude of the quantity measured. Letting  $\sigma^2$  represent the variance of  $y_i$ , one could assume a simple linear relation

$$\sigma^2 = kx_i , \quad (\text{eqn 4.3})$$

in which case Equation 4.2 can be transformed by dividing by  $\sqrt{x_i}$  . This will give a constant variance model and help to normalize the residuals. However, this procedure will not work if the data displays a variance that first increases and then decreases as the true content increases.

TABLE 13  
REGRESSION RESULTS FOR FE

Data	Model	$r^2$	$B_0$	$\sigma_{B_0}$	$B_1$	$\sigma_{B_1}$	n
Elmendorf	1-Lin	.81	-2.68	1.55	.527	.024	116
Langley	1-Lin	.85	-3.02	2.17	.618	.035	58
Myrtle Beach	1-Lin	.96	-4.57	1.17	.629	.018	51
Pensacola	1-Lin	.95	-1.75	.85	.667	.014	116
All Loc	1-Lin	.87	-2.43	.79	.596	.013	341
LanMyrPen	1-Lin	.92	-2.47	.76	.637	.013	231
All Loc	1-Quad	.87	*	*	*	*	341
Corr Means	2-Lin	.87	-.36	1.64	.507	.034	36
Verif Means	2-Lin	.97	-9.76	3.01	.719	.040	12
All Loc Means	2-Lin	.90	-1.92	1.59	.570	.028	48
LMP Means	2-Lin	.96	-2.09	1.33	.617	.022	36
PWMA <sup>2</sup> -Dash-3 <sup>2</sup>	2-Lin	.82	*	*	*	*	48
PWMA-Dash-3 <sup>2</sup>	2-Lin	.85	*	*	*	*	48
PWMA <sup>2</sup> -Dash-3	2-Lin	.77	*	*	*	*	48

\*-denotes not included due to little or no  $r^2$  improvement.

TABLE 14  
REGRESSION RESULTS FOR AG

Data	Model	$r^2$	$B_0$	$\sigma_{B_0}$	$B_1$	$\sigma_{B_1}$	n
Elmendorf	1-Lin	.74	.49	.27	.466	.026	118
Langley	1-Lin	.92	-.37	.26	.574	.022	58
Myrtle Beach	1-Lin	.88	.22	.32	.535	.028	51
Pensacola	1-Lin	.92	.24	.20	.685	.019	117
All Loc	1-Lin	.82	.29	.15	.559	.014	344
LanMyrPen	1-Lin	.87	.19	.17	.605	.015	229
All Loc	1-Quad	.84	*	*	*	*	344
Corr Means	2-Lin	.91	.02	.37	.539	.029	36
Verif Means	2-Lin	.95	-.45	.38	.690	.050	12
All Loc Means	2-Lin	.91	.11	.30	.542	.025	48
LMP Means	2-Lin	.91	.16	.36	.567	.030	36
PWMA <sup>2</sup> -Dash-3 <sup>2</sup>	2-Lin	.81	*	*	*	*	48
PWMA-Dash-3 <sup>2</sup>	2-Lin	.76	*	*	*	*	48
PWMA <sup>2</sup> -Dash-3	2-Lin	.83	*	*	*	*	48

\*-denotes not included due to little or no  $r^2$  improvement.

TABLE 15  
REGRESSION RESULTS FOR AL

Data	Model	$r^2$	$B_0$	$\sigma_{B_0}$	$B_1$	$\sigma_{B_1}$	n
Elmendorf	1-Lin	.60	.88	.73	.428	.032	116
Langley	1-Lin	.67	1.65	1.00	.650	.060	58
Myrtle Beach	1-Lin	.80	2.14	.80	.618	.045	48
Pensacola	1-Lin	.59	5.25	.70	.399	.031	118
All Loc	1-Lin	.57	3.19	.44	.442	.021	340
Lan.MyrPen	1-Lin	.31	7.89	.55	.250	.025	231
All Loc	1-Quad	.59	*	*	*	*	340
Corr Means	2-Lin	.75	3.21	1.10	.435	.045	34
Verif Means	2-Lin	.84	1.00	1.30	.723	.098	12
All Loc Means	2-Lin	.75	3.15	.87	.451	.039	46
LMP Means	2-Lin	.79	3.74	.93	.482	.043	34
PWMA <sup>2</sup> -Dash-3 <sup>2</sup>	2-Lin	.65	*	*	*	*	46
PWMA-Dash-3 <sup>2</sup>	2-Lin	.60	*	*	*	*	46
PWMA <sup>2</sup> -Dash-3	2-Lin	.69	*	*	*	*	46

\*-denotes not included due to little or no  $r^2$  improvement.

TABLE 16  
REGRESSION RESULTS FOR CR

Data	Model	$r^2$	$B_0$	$\sigma_{B_0}$	$B_1$	$\sigma_{B_1}$	n
Elmendorf	1-Lin	.70	.58	.23	.540	.033	118
Langley	1-Lin	.91	-.19	.26	.788	.033	59
Myrtle Beach	1-Lin	.92	.48	.23	.804	.036	49
Pensacola	1-Lin	.96	-.19	.12	.809	.016	119
All Loc	1-Lin	.83	.20	.12	.711	.017	345
LanMyrPen	1-Lin	.93	.03	.11	.792	.015	229
All Loc	1-Quad	.84	*	*	*	*	345
Corr Means	2-Lin	.90	.21	.35	.738	.042	36
Verif Means	2-Lin	.95	-.23	.33	.873	.060	12
All Loc Means	2-Lin	.90	-.06	.28	.738	.036	48
LMP Means	2-Lin	.97	-.29	.20	.822	.026	36
PWMA <sup>2</sup> -Dash-3 <sup>2</sup>	2-Lin	.81	*	*	*	*	48
PWMA-Dash-3 <sup>2</sup>	2-Lin	.83	*	*	*	*	48
PWMA <sup>2</sup> -Dash-3	2-Lin	.80	*	*	*	*	48

\*-denotes not included due to little or no  $r^2$  improvement.



TABLE 17  
REGRESSION RESULTS FOR CU

Data	Model	$r^2$	$B_0$	$\sigma_{B_0}$	$B_1$	$\sigma_{B_1}$	n
Elmendorf	1-Lin	.78	-.75	.96	.559	.028	117
Langley	1-Lin	.82	-2.02	1.38	.651	.041	57
Myrtle Beach	1-Lin	.92	-2.66	.88	.737	.022	51
Pensacola	1-Lin	.90	-2.66	.88	.737	.022	118
All Loc	1-Lin	.84	-2.19	.56	.667	.016	343
LanMyrPen	1-Lin	.89	-2.73	.62	.713	.017	230
All Loc	1-Quad	.84	*	*	*	*	343
Corr Means	2-Lin	.91	-1.30	1.42	.652	.035	36
Verif Means	2-Lin	.99	-2.70	.48	.638	.016	12
All Loc Means	2-Lin	.92	-1.93	1.08	.658	.028	48
LMP Means	2-Lin	.94	-2.40	1.19	.699	.031	36
PWMA <sup>2</sup> -Dash-3 <sup>2</sup>	2-Lin	.86	*	*	*	*	48
PWMA-Dash-3 <sup>2</sup>	2-Lin	.86	*	*	*	*	48
PWMA <sup>2</sup> -Dash-3	2-Lin	.84	*	*	*	*	48

\*-denotes not included due to little or no  $r^2$  improvement.

TABLE 18  
REGRESSION RESULTS FOR MG

Data	Model	$r^2$	$B_0$	$\sigma_{B_0}$	$B_1$	$\sigma_{B_1}$	n
Elmendorf	1-Lin	.81	-3.39	.66	.526	.023	116
Langley	1-Lin	.85	-3.12	.99	.647	.036	57
Myrtle Beach	1-Lin	.82	-2.97	1.15	.586	.040	51
Pensacola	1-Lin	.87	.20	.62	.648	.024	115
All Loc	1-Lin	.76	-1.70	.49	.578	.018	339
LanMyrPen	1-Lin	.35	-6.35	.80	.317	.028	231
All Loc	1-Quad	-	*	*	*	*	339
Corr Means	2-Lin	.84	-1.98	1.53	.584	.046	34
Verif Means	2-Lin	.80	-2.65	2.16	.619	.097	12
All Loc Means	2-Lin	.84	-2.06	1.19	.587	.038	46
LMP Means	2-Lin	.84	-1.57	1.41	.602	.045	34
PWMA <sup>2</sup> -Dash-3 <sup>2</sup>	2-Lin	.79	*	*	*	*	46
PWMA-Dash-3 <sup>2</sup>	2-Lin	.79	*	*	*	*	46
PWMA <sup>2</sup> -Dash-3	2-Lin	.77	*	*	*	*	46

\*-denotes not included due to little or no  $r^2$  improvement.

TABLE 19  
REGRESSION RESULTS FOR NI

Data	Model	$r^2$	$B_0$	$\sigma_{B_0}$	$B_1$	$\sigma_{B_1}$	n
Elmendorf	1-Lin	.80	-.48	.59	.553	.026	118
Langley	1-Lin	.91	-.16	.62	.617	.026	59
Myrtle Beach	1-Lin	.95	-1.66	.57	.750	.026	50
Pensacola	1-Lin	.95	.44	.32	.639	.014	119
All Loc	1-Lin	.87	-.22	.30	.619	.013	346
Lan.MyrPen	1-Lin	.93	-.05	.28	.651	.012	229
All Loc	1-Quad	.88	*	*	*	*	346
Corr Means	2-Lin	.92	.88	.65	.569	.029	36
Verif Means	2-Lin	.98	-3.68	.70	.793	.032	12
All Loc Means	2-Lin	.92	.18	.59	.603	.026	48
LMP Means	2-Lin	.97	.37	.42	.638	.018	36
PWMA <sup>2</sup> -Dash-3 <sup>2</sup>	2-Lin	.89	*	*	*	*	48
PWMA-Dash-3 <sup>2</sup>	2-Lin	.82	*	*	*	*	48
PWMA <sup>2</sup> -Dash-3	2-Lin	.85	*	*	*	*	48

\*-denotes not included due to little or no  $r^2$  improvement.

### 1. Regression Using All Data Points Individually (Model 1)

Seven different regressions were run where all data points from all locations were used. The first four of these were run by using a simple linear model on each

TABLE 20  
REGRESSION RESULTS FOR SI

Data	Model	$r^2$	$B_0$	$\sigma_{B_0}$	$B_1$	$\sigma_{B_1}$	n
Elmendorf	1-Lin	.46	-.14	.93	.346	.035	115
Langley	1-Lin	.66	-.95	1.08	.452	.043	59
Myrtle Beach	1-Lin	.86	-.91	.55	.337	.019	50
Pensacola	1-Lin	.67	-.17	.63	.400	.026	115
All Loc	1-Lin	.60	-.31	.43	.375	.017	339
LanMyrPen	1-Lin	.66	-.28	.48	.394	.019	232
All Loc	1-Quad	.61	*	*	*	*	339
Corr Means	2-Lin	.82	-1.01	.65	.298	.024	36
Verif Means	2-Lin	.94	-1.11	1.02	.490	.040	12
All Loc Means	2-Lin	.75	-.67	.74	.329	.027	48
LMP Means	2-Lin	.77	-.80	.93	.356	.033	36
PWMA <sup>2</sup> -Dash-3 <sup>2</sup>	2-Lin	.67	*	*	*	*	48
PWMA-Dash-3 <sup>2</sup>	2-Lin	.68	*	*	*	*	48
PWMA <sup>2</sup> -Dash-3	2-Lin	.63	*	*	*	*	48

\*-denotes not included due to little or no  $r^2$  improvement.

location and the data then used to gain a parametric understanding of the scatterplots presented earlier. Non-parametric results in Tables 22 - 24 were derived from these regressions. Table 22 ranks the slopes for each element by location and shows Elmendorf to have a smaller slope with six of the nine elements (explaining the earlier scatterplot results). It also shows Pensacola to have a higher slope than the other locations in five of the elements. The rankings of the standard deviations of the slopes are given in Table 23 . It was found to be smallest most often with Pensacola, with Elmendorf exhibiting the second smallest standard deviation. Table 24 ranks  $r^2$  and shows Elmendorf to have a lower  $r^2$  in seven of the nine elements.

TABLE 21  
REGRESSION RESULTS FOR TI

Data	Model	$r^2$	$B_0$	$\sigma_{B_0}$	$B_1$	$\sigma_{B_1}$	n
Elmendorf	1-Lin	.82	-1.46	.43	.604	.026	117
Langley	1-Lin	.76	.12	.72	.564	.042	59
Myrtle Beach	1-Lin	.92	-1.15	.44	.648	.027	50
Pensacola	1-Lin	.86	.17	.35	.639	.024	117
All Loc	1-Lin	.81	-.41	.25	.602	.016	343
LanMyrPen	1-Lin	.83	.02	.28	.609	.018	230
All Loc	1-Quad	.81	*	*	*	*	343
Corr Means	2-Lin	.88	.00	.54	.584	.037	36
Verif Means	2-Lin	.99	-2.08	.40	.692	.024	12
All Loc Means	2-Lin	.91	-.42	.44	.607	.028	48
LMP Means	2-Lin	.95	-.03	.40	.618	.025	36
PWMA <sup>2</sup> -Dash-3 <sup>2</sup>	2-Lin	.85	*	*	*	*	48
PWMA-Dash-3 <sup>2</sup>	2-Lin	.82	*	*	*	*	48
PWMA <sup>2</sup> -Dash-3	2-Lin	.83	*	*	*	*	48

\*-denotes not included due to little or no  $r^2$  improvement.

The remaining three regressions were used to determine the best way to fit the data from the combination of locations. A combination using all locations except Elmendorf was investigated because of Elmendorf's significantly smaller slope. For most elements, (all except Al and Mg),  $r^2$  increased when Elmendorf was not included. No more than a .02 improvement was gained by using a quadratic regression on the data. Because of this small gain, it was decided not to pursue this regression model. Other regression variations were tried in the sample and level means model described next.



TABLE 22  
RANK OF SLOPES FOR INDIVIDUAL LOCATION REGRESSIONS

	Fe	Ag	Al	Cr	Cu	Mg	Ni	Si	Ti
Elm	4	4	3	4	4	4	4	3	3
Lan	3	2	1	3	3	2	3	1	4
Myr	2	3	2	2	2	3	1	4	1
Pen	1	1	4	1	1	1	2	2	2

Rankings highest(1) to lowest(4)

TABLE 23  
RANK OF SLOPE STANDARD DEVIATIONS FOR LOCATIONS

	Fe	Ag	Al	Cr	Cu	Mg	Ni	Si	Ti
Elm	3	3	2	2	2	1	2	3	1
Lan	4	2	4	2	4	3	2	4	4
Myr	2	4	3	4	2	4	2	1	3
Pen	1	1	1	1	1	2	1	2	2

Rankings smallest(1) to largest(4)

TABLE 24  
RANK OF  $R^2$  FOR LOCATION REGRESSIONS

	Fe	Ag	Al	Cr	Cu	Mg	Ni	Si	Ti
Elm	4	4	3	4	4	4	4	4	3
Lan	3	1	2	3	3	2	3	3	4
Myr	1	3	1	2	1	3	1	1	1
Pen	2	1	4	1	2	1	1	2	2

Rankings largest(1) to smallest(4)

## 2. Regression Using Sample and Level Means (Model 2)

Due to the disparity in the number of samples provided by each location, (from a low of 51 to a high of 119), a method was needed to eliminate the skewing of results toward the locations with more data points. By taking the means for each of the three verification levels and of the nine correlation samples, all four locations would be equally weighted. This approach allowed a total of twelve means (9 correlation and 3 verification) to be provided from each location. Several regressions were conducted using this approach. Linear regressions were conducted on the verification level means alone, the correlation sample means, on the combined means, and on all means except those from Elmendorf. Linear regressions on transformations of the combined location model were also investigated. From Tables 13 - 21 , it can be seen that the slopes for verification level regressions were often high in comparison to the other regressions. The low number of data points (three clusters of four points each) probably contributed to this. The correlation sample means regression was non-descript and quite similar to the regression utilizing model 1 for many of the elements. The model 2 regressions using the mean values from all locations and using mean values from all locations but Elmendorf are also very similar to their counterpart model 1 regressions that utilize all points. The similarity can be seen in the summary of equations table presented in Table 25 . The equations shown have the highest  $r^2$  for each respective model. The supporting data either consisted of data from all locations or all locations except Elmendorf (indicated by LMP). The  $r^2$  values using the means (model 2) is greater than or equal to those obtained using all points (model 1) in every instance. Improvements to the  $r^2$  values were investigated through three linear models which used transformations of the data, these were:

$$PWMA^2 = B_0 + B_1 \text{Dash-3}^2 + e , \quad (\text{eqn 4.4})$$

$$PWMA = B_0 + B_1 \text{Dash-3}^2 + e , \quad (\text{eqn 4.5})$$

$$PWMA^2 = B_0 + B_1 \text{Dash-3} + e . \quad (\text{eqn 4.6})$$

Throughout all of the regressions, a recurring problem of violating basic model assumptions was observed. This is not to imply the equations are not unbiased estimators, but only that they may not be the best estimators.

The common data transformation technique described at the beginning of the section was attempted but it had little success in normalizing residuals or gaining constant variance. Four elements (Al, Cr, Ni, and Ti) did attain a constant variance, and five elements (Fe, Al, Cr, Mg, and Ti) achieved normalized residuals. Only the elements Al and Cr met both assumptions of constant variance and normalized residuals. With only two elements meeting both assumptions and four others meeting only one after using the transformation derived from Equation 4.3, it was decided not to pursue the transformation farther. This decision was supported by taking into account the small improvement gained in meeting the assumptions at the expense of the complexities that would be introduced into the equations for the oil analyst.

TABLE 25  
REGRESSION EQUATIONS FOR MODEL 1 AND MODEL 2

	1-All Points	Loc	r <sup>2</sup>		2-Means	Loc	r <sup>2</sup>
Fe	P = -2.47 + .637D	LMP	.92		P = -2.09 + .617D	LMP	.96
Ag	P = .19 + .605D	LMP	.87		P = .16 + .567D	LMP	.91
Al	P = 3.19 + .442D	All	.57		P = 3.74 + .482D	LMP	.79
Cr	P = .03 + .792D	LMP	.93		P = -.29 + .822D	LMP	.97
Cu	P = -2.73 + .713D	LMP	.89		P = -2.40 + .699D	LMP	.94
Mg	P = -1.70 + .578D	All	.76		P = -2.06 + .587D	All	.84
Ni	P = -.05 + .651D	LMP	.93		P = .37 + .638D	LMP	.84
Si	P = -.28 + .394D	LMP	.66		P = -.80 + .356D	LMP	.77
Ti	P = .02 + .609D	LMP	.83		P = -.03 + .618D	LMP	.95

## V. SUMMARY AND CONCLUSIONS

The Joint Oil Analysis Program has reached an important milestone with the addition of the Portable Wear Metal Analyzer. Strong relationships were shown to exist by this analysis between the measurements taken by the prototype PWMA and the A/E35U-3. The analysis was based on data from a 1985 field evaluation of prototype PWMA's. Although the data was not obtained in a consistent fashion by the laboratories, it was useful in determining accuracy within and between the laboratories. A subsequent analysis similar to this one is merited when production PWMA's and supporting parts are in use. The equations below describe the best estimate of the relationship between the Dash-3 and prototype PWMA readings. The equations could be used in making conversions from the *JOAP Laboratory Manual*. Any values that result in a negative translation should be regarded as zero.

TABLE 26  
RECOMMENDED EQUATIONS FOR A/E35U-3 TO PWMA CONVERSIONS

Fe	$PWMA = -2.09 + .617(\text{Dash-3})$
Ag	$PWMA = .16 + .567(\text{Dash-3})$
Al	$PWMA = 3.74 + .482(\text{Dash-3})$
Cr	$PWMA = -.29 + .822(\text{Dash-3})$
Cu	$PWMA = -2.40 + .699(\text{Dash-3})$
Mg	$PWMA = -2.06 + .587(\text{Dash-3})$
Ni	$PWMA = .37 + .638(\text{Dash-3})$
Si	$PWMA = -.80 + .356(\text{Dash-3})$
Ti	$PWMA = -.03 + .618(\text{Dash-3})$

The equations presented are unbiased estimators when a simple linear relationship is assumed (although they do contain violations of homoscedascity and normalized residuals). The ability of the equations to describe the data varied, but

seven of the nine elements had  $r^2$  values above .80 (Al at .79 and Si at .77 were the exceptions). These values were obtained using prototype instruments that were using prototype graphite furnace tubes and were therefore considered quite good. One of the four locations consistently had a slope less than the others, causing it to be dropped from the final analysis for seven of the elements. This improved the  $r^2$  values in each of those elements.

Items that may have influenced the data used included the non-production graphite furnace tubes, the particle size capabilities of each instrument, the nature of the correlation samples, and the several factors mentioned in Chapter II. The furnace tubes were found to have statistically significant differences at each of the locations, but they did not appear to have a practical difference for the oil analyst. Further analysis using production model tubes will serve to clarify this area. In regards to particle size, the Dash-3 can only measure particles less than ten micrometers in size, while the PWMA can measure particles up to twenty micrometers. It can be deduced from this that the PWMA/Dash-3 functional relationship is directly dependent on particle size. Therefore a sample with all particles less than ten micrometers in size should show a very strong relationship between instruments. However, it is possible for a sample to contain a majority of its particles in the ten to twenty micrometer range (or higher) and thereby yield readings not consistent with the equations derived. The correlation samples were manufactured using a blend of oils and enriched with powdered organo-metallic concentrates to obtain measureable wearmetal levels. The room for inconsistencies due to the type oil used for instrument calibration with the type in the correlation sample, and due to particle sizes in the samples leaves this as an area for further scrutiny.



# APPENDIX A GRAPHITE TUBE CODED SCATTERPLOTS OF VERIFICATION AND CORRELATION SAMPLES

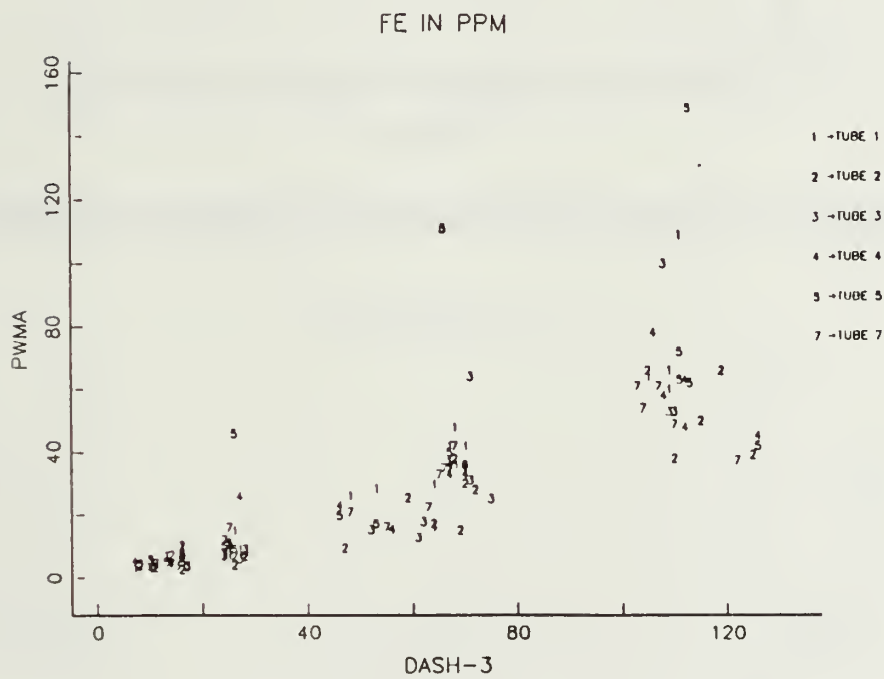


Figure A.1 Graphite Tube Scatterplot-Location:Elmendorf-Element:Fe.

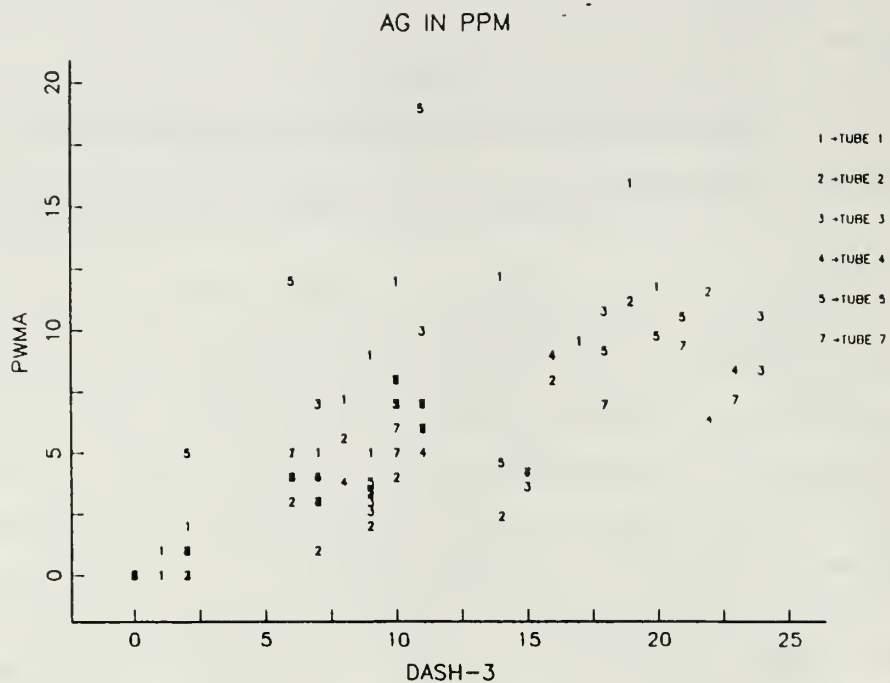
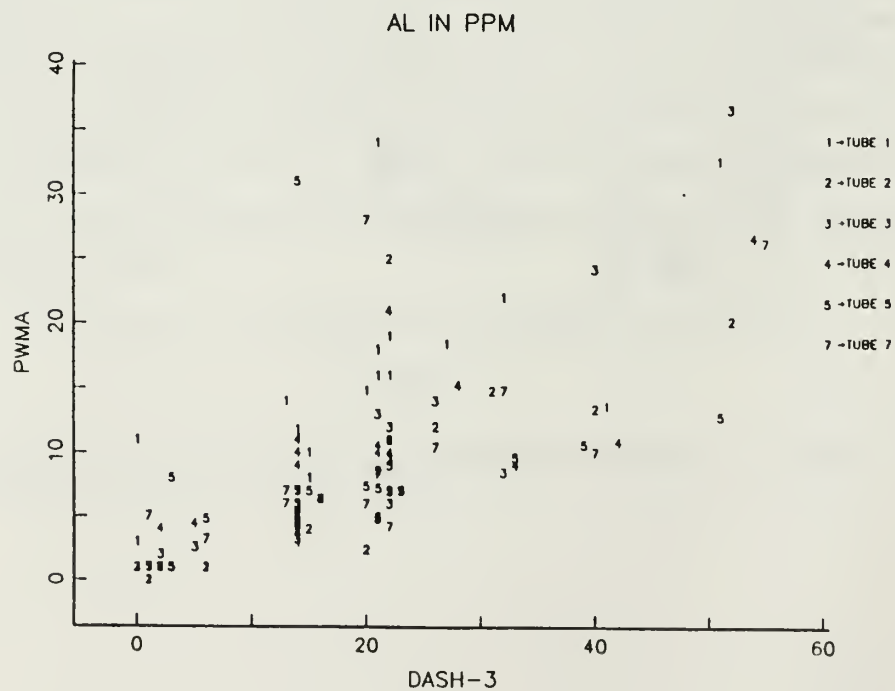


Figure A.2 Graphite Tube Scatterplot-Location:Elmendorf-Element:Ag.



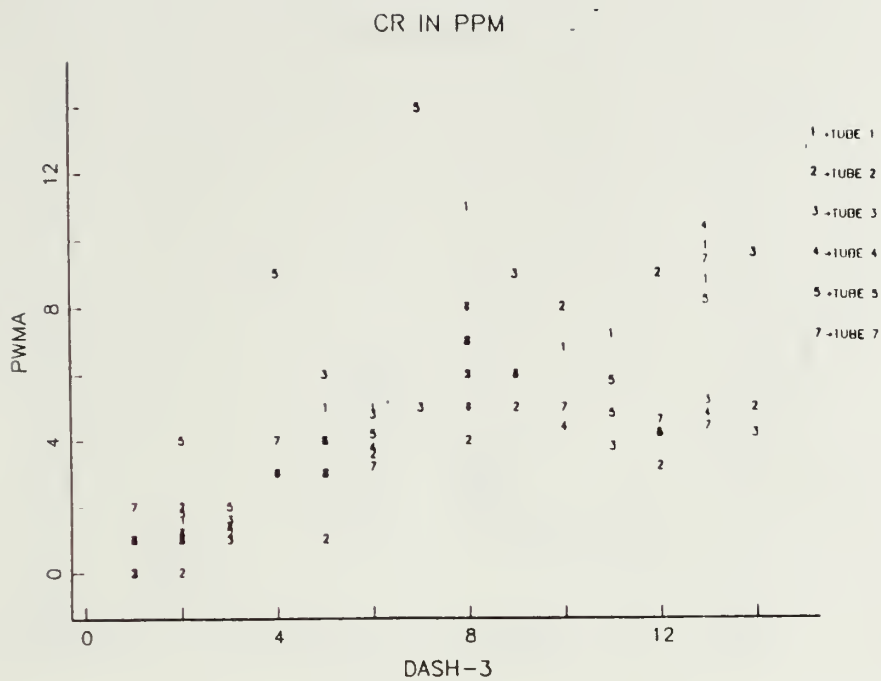


Figure A.4 Graphite Tube Scatterplot-Location:Elmendorf-Element:Cr.

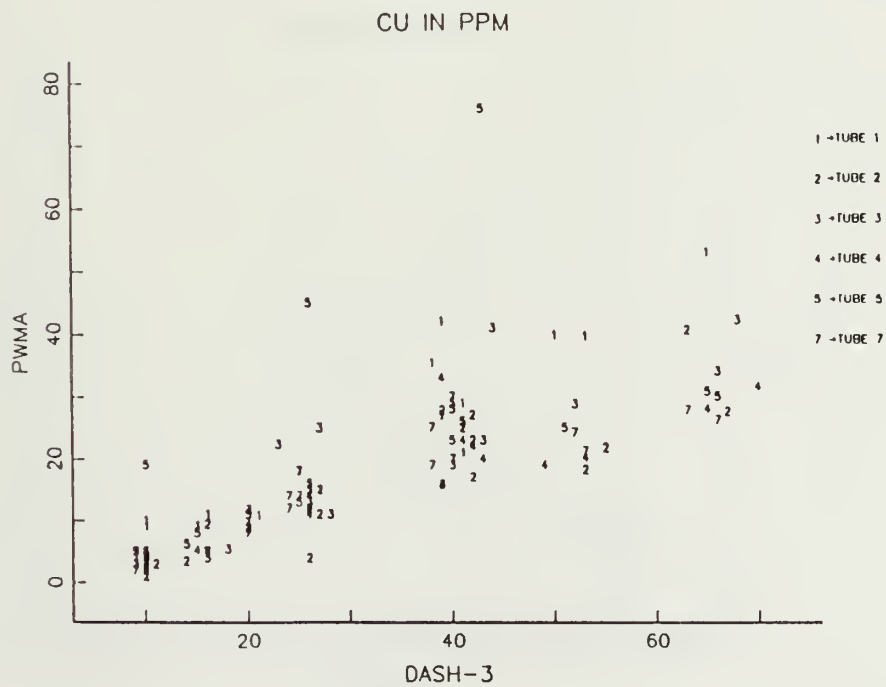


Figure A.5 Graphite Tube Scatterplot-Location:Elmendorf-Element:Cu.

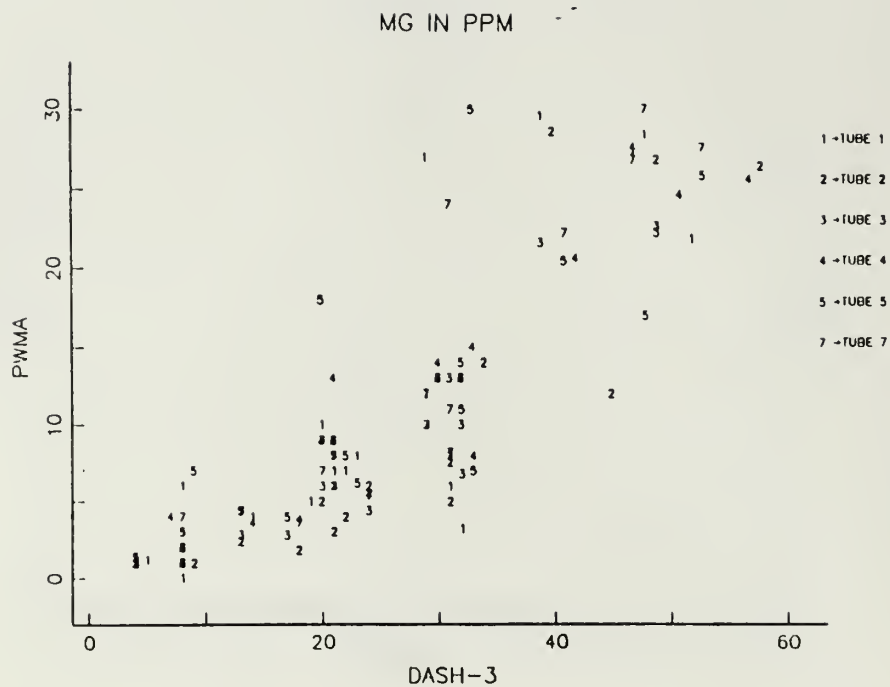


Figure A.6 Graphite Tube Scatterplot-Location:Elmendorf-Element:Mg.

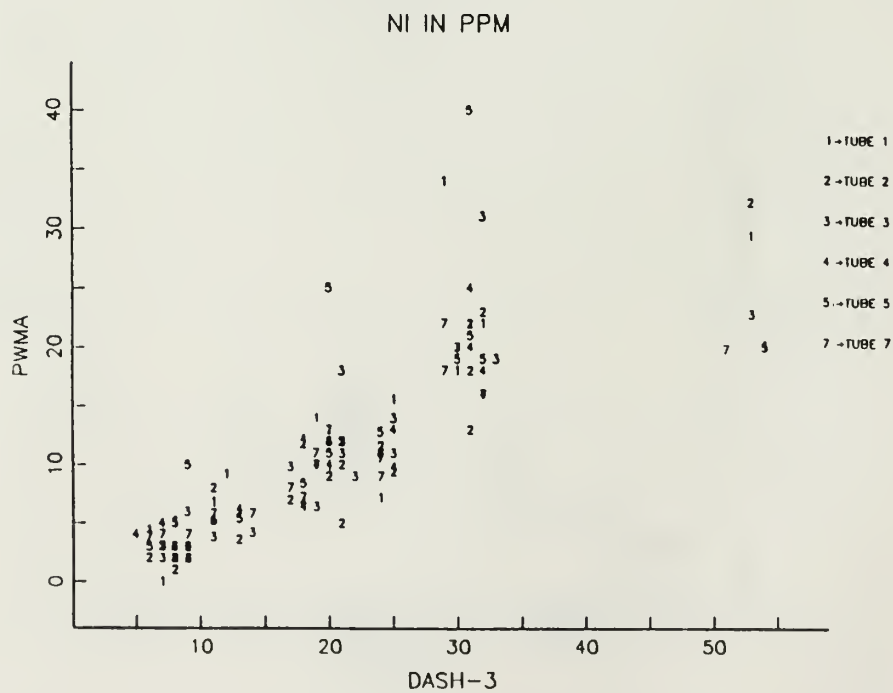


Figure A.7 Graphite Tube Scatterplot-Location:Elmendorf-Element:Ni.

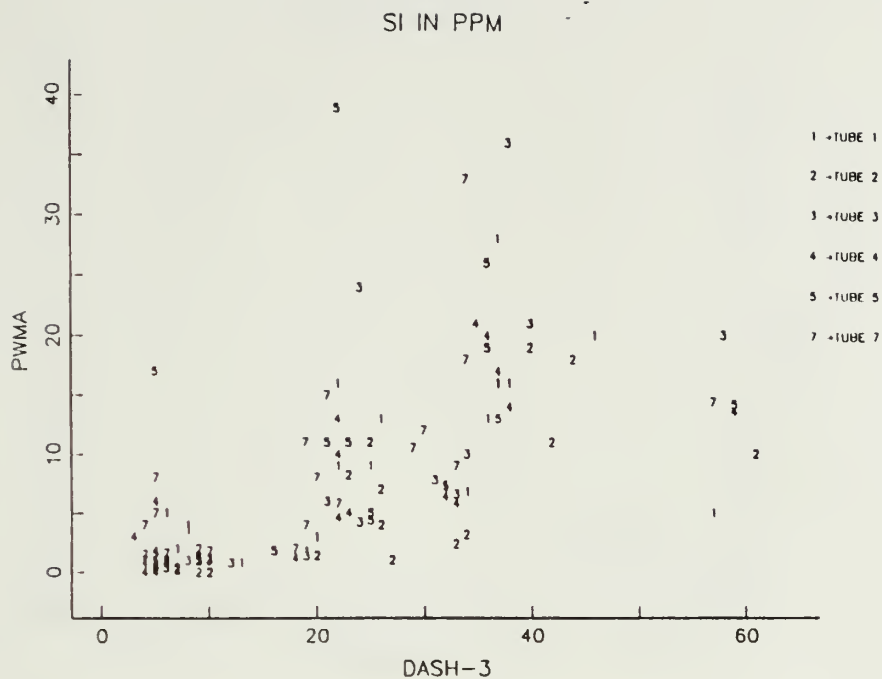


Figure A.8 Graphite Tube Scatterplot-Location:Elmendorf-Element:Si.

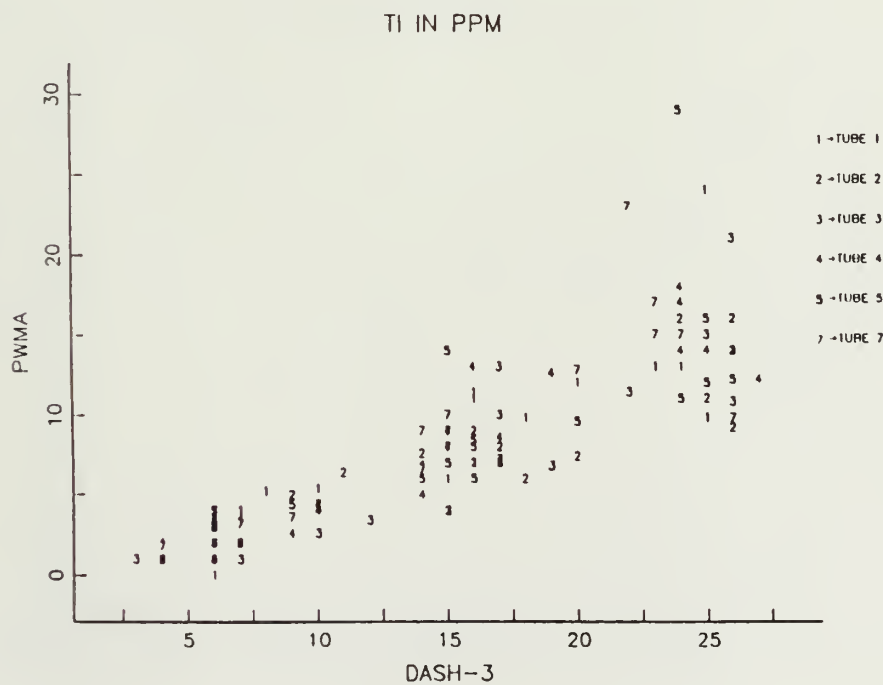


Figure A.9 Graphite Tube Scatterplot-Location:Elmendorf-Element:Ti.



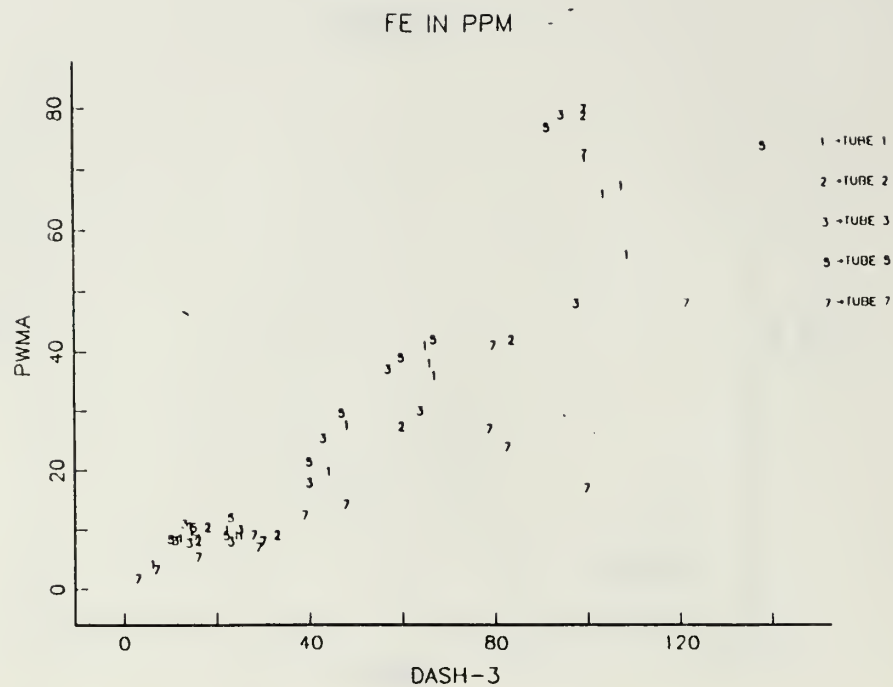


Figure A.10 Graphite Tube Scatterplot-Location:Langley-Element:Fe.

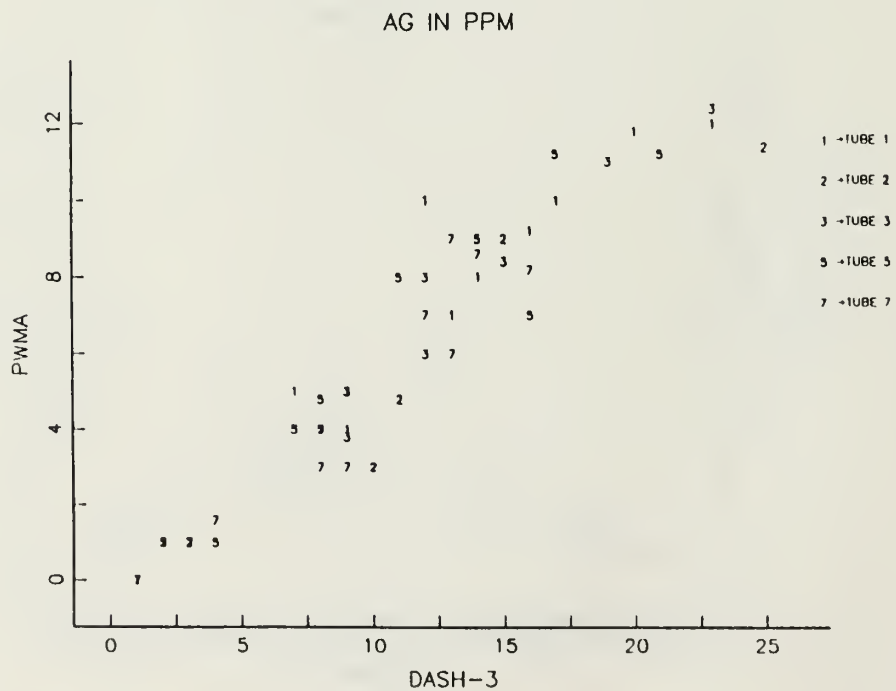


Figure A.11 Graphite Tube Scatterplot-Location:Langley-Element:Ag.

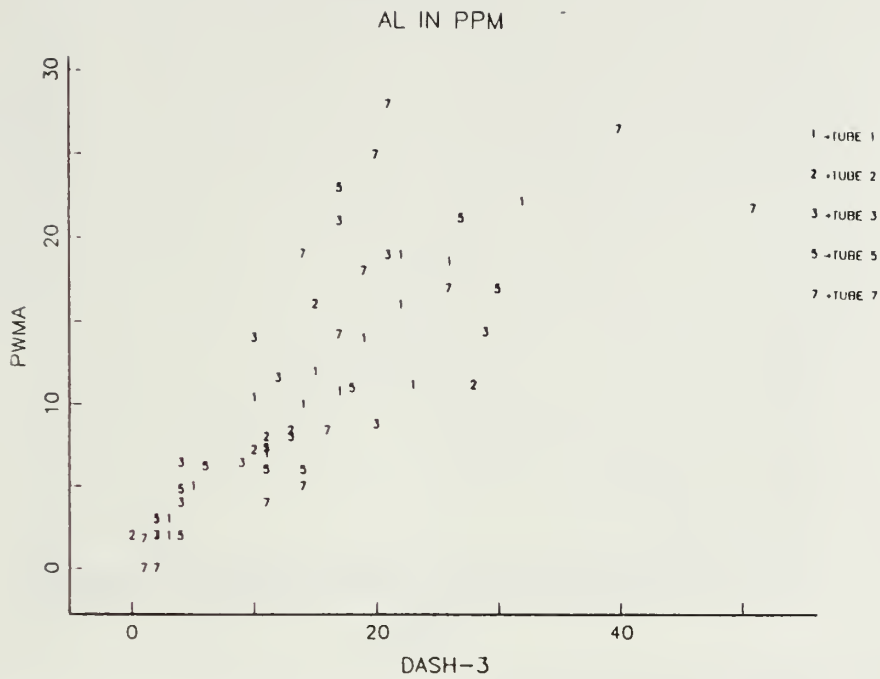


Figure A.12 Graphite Tube Scatterplot-Location:Langley-Element:Al.

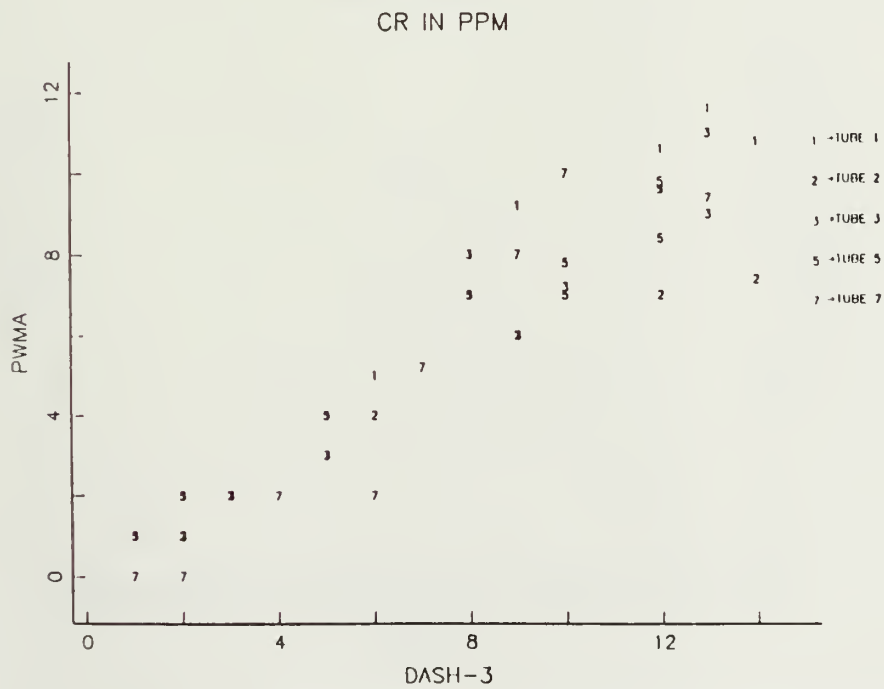


Figure A.13 Graphite Tube Scatterplot-Location:Langley-Element:Cr.

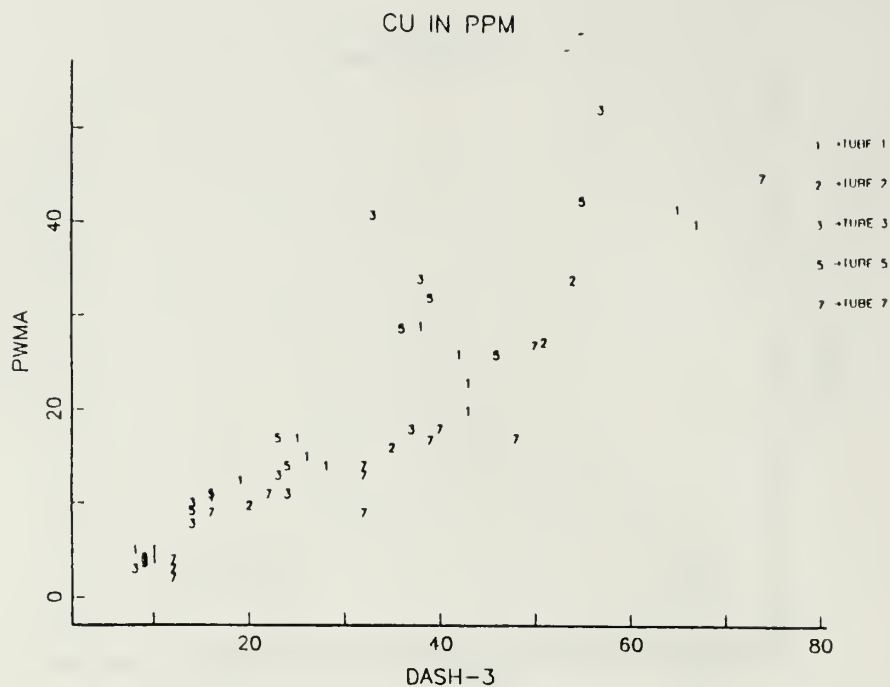


Figure A.14 Graphite Tube Scatterplot-Location:Langley-Element:Cu.

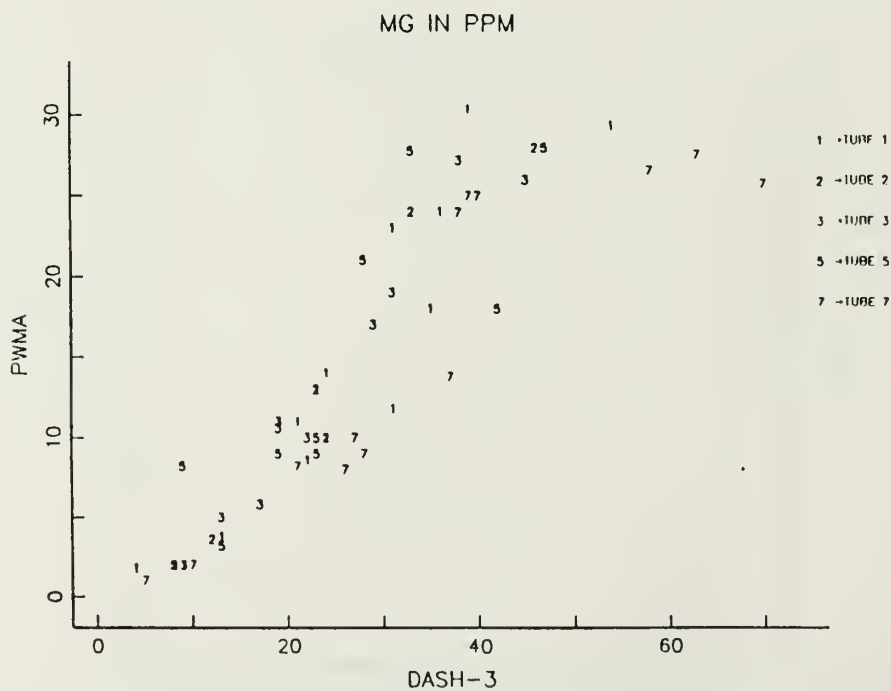


Figure A.15 Graphite Tube Scatterplot-Location:Langley-Element:Mg.

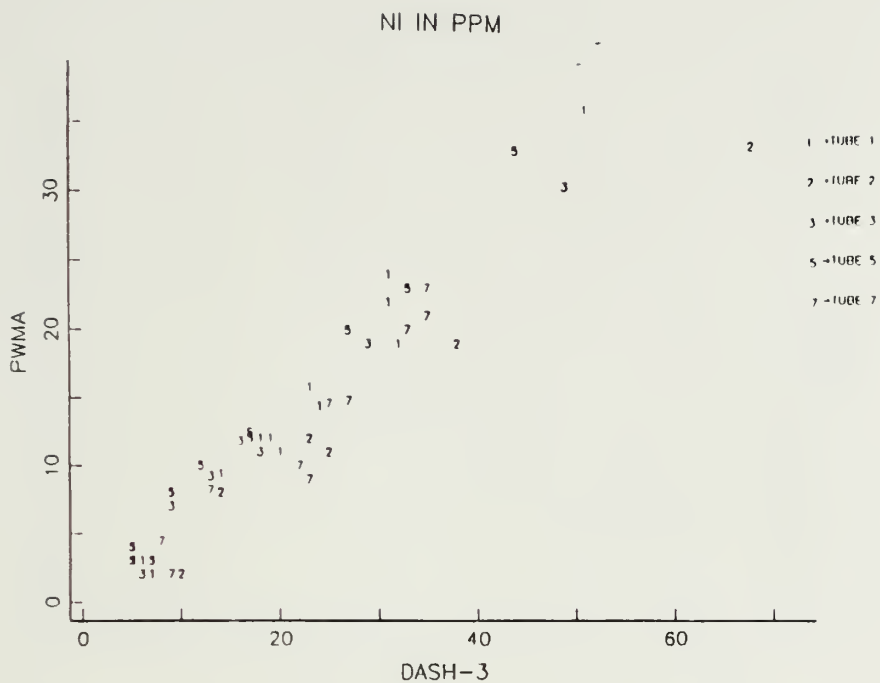


Figure A.16 Graphite Tube Scatterplot-Location:Langley-Element:Ni.

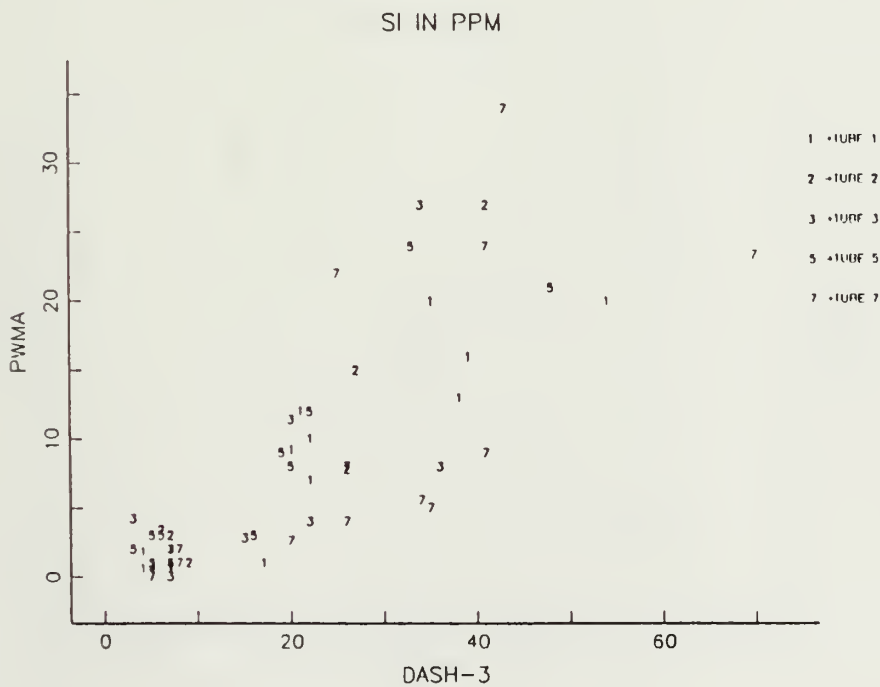


Figure A.17 Graphite Tube Scatterplot-Location:Langley-Element:Si.

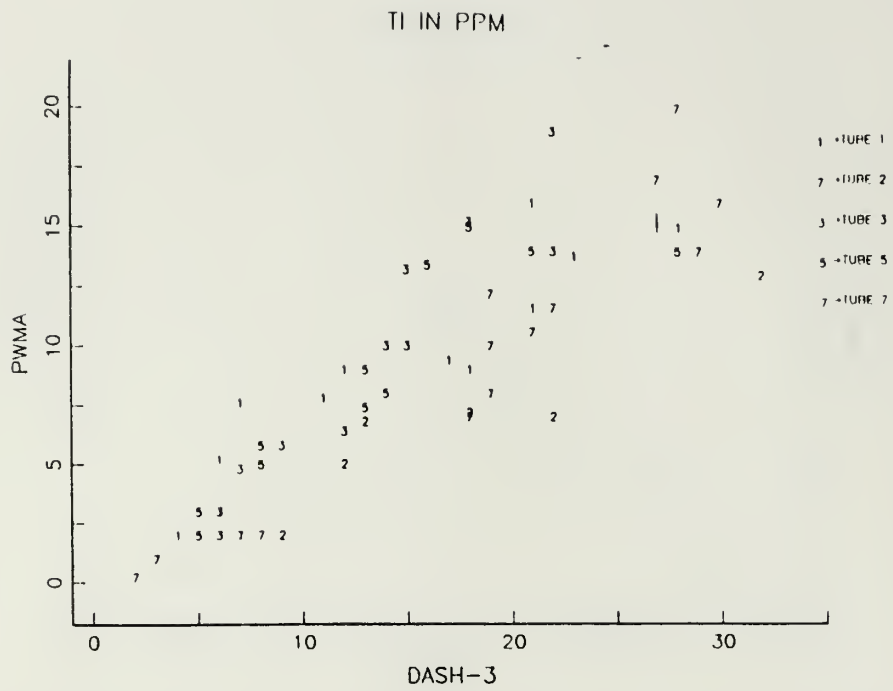


Figure A.18 Graphite Tube Scatterplot-Location:Langley-Element:Ti.

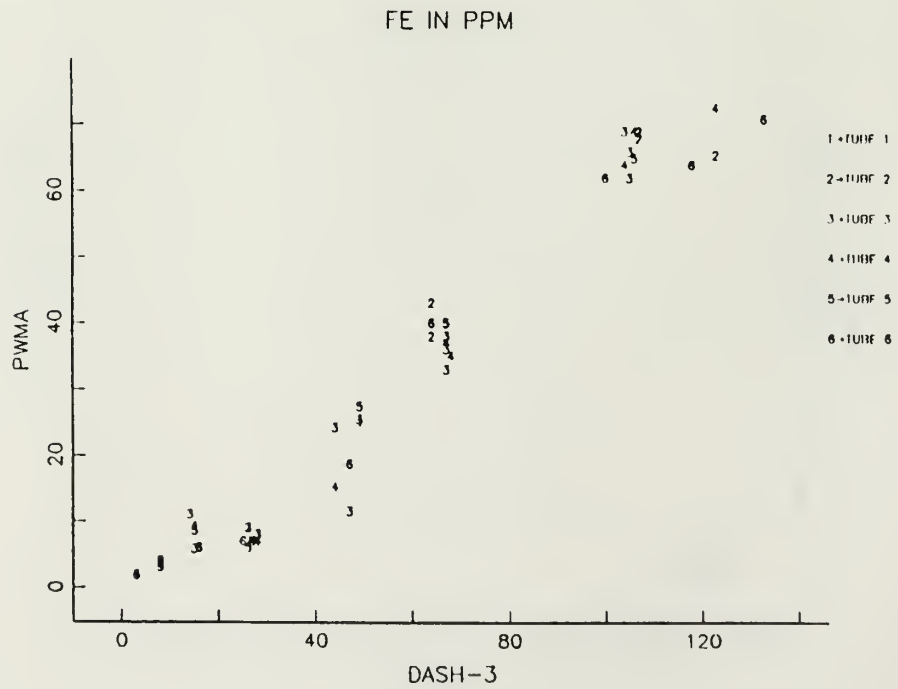


Figure A.19 Graphite Tube Scatterplot-Location:Myrtle Beach-Element:Fe.



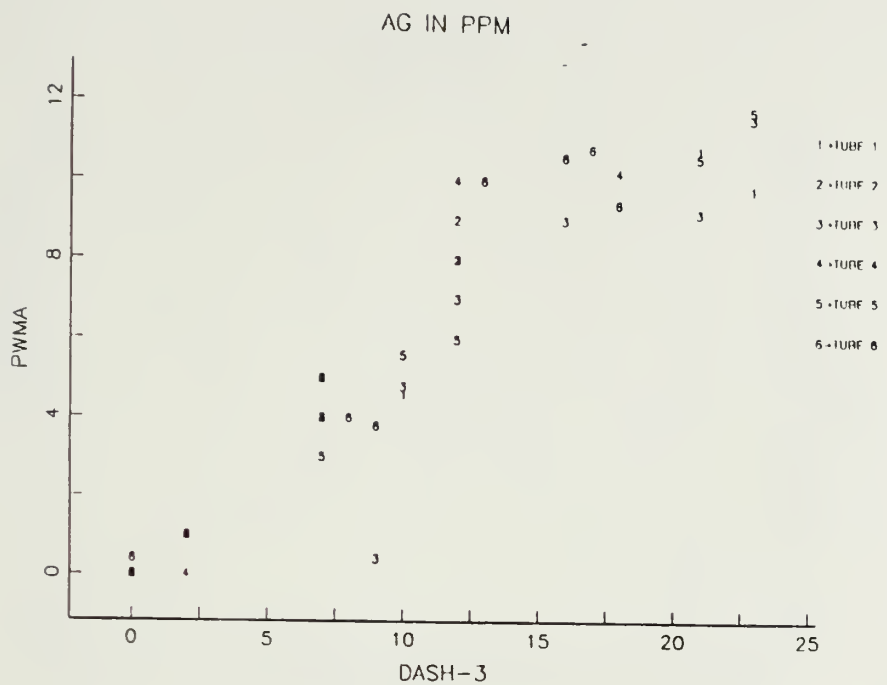


Figure A.20 Graphite Tube Scatterplot-Location:Myrtle Beach-Element:Ag.

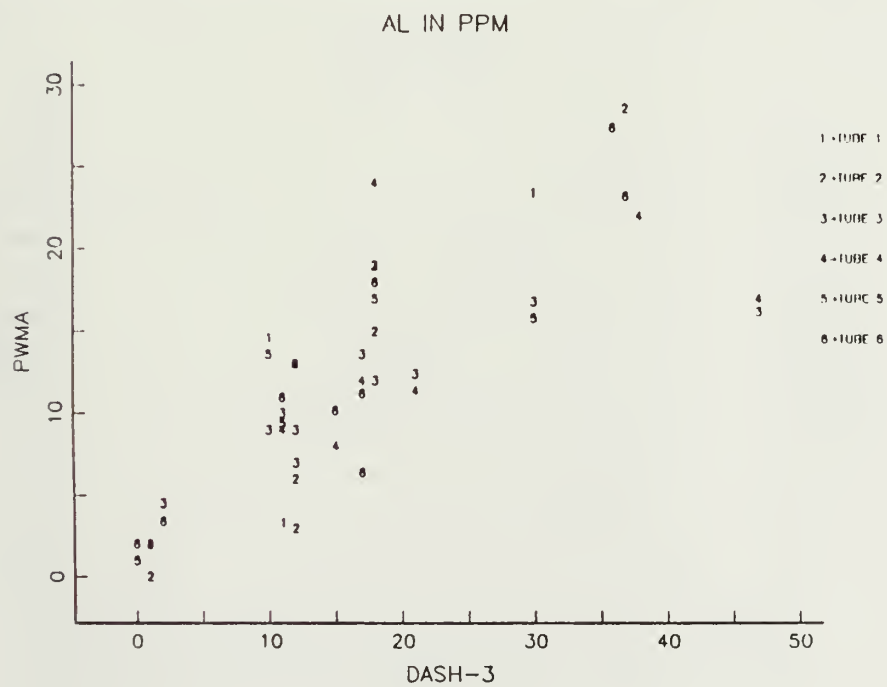


Figure A.21 Graphite Tube Scatterplot-Location:Myrtle Beach-Element:Al.

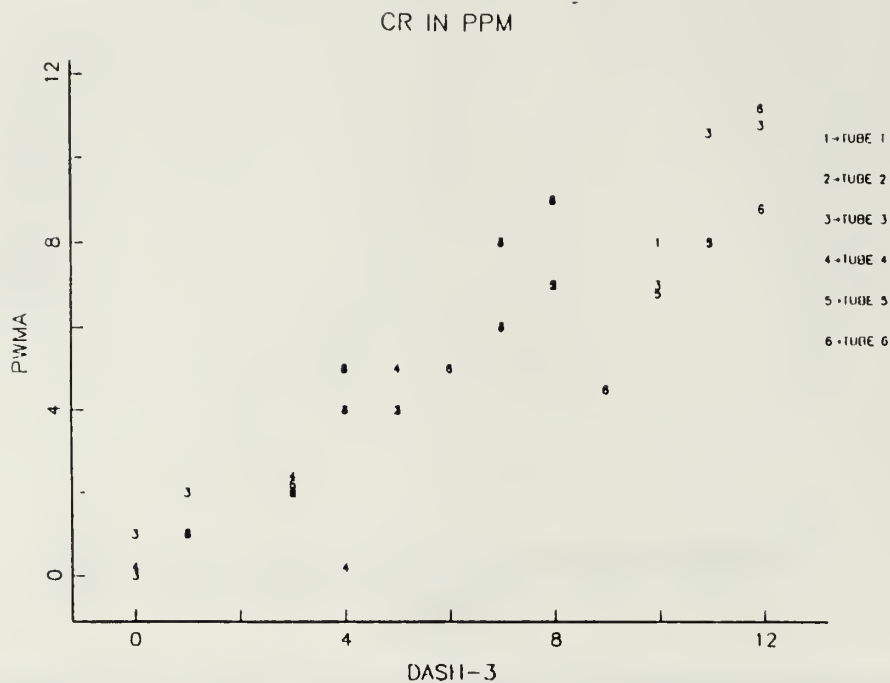


Figure A.22 Graphite Tube Scatterplot-Location:Myrtle Beach-Element:Cr.

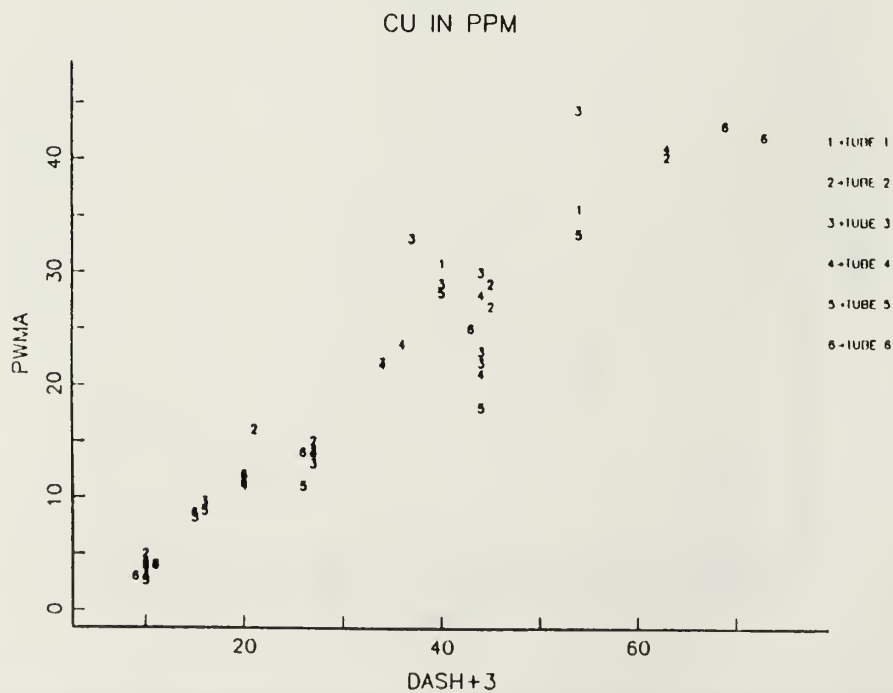


Figure A.23 Graphite Tube Scatterplot-Location:Myrtle Beach-Element:Cu.

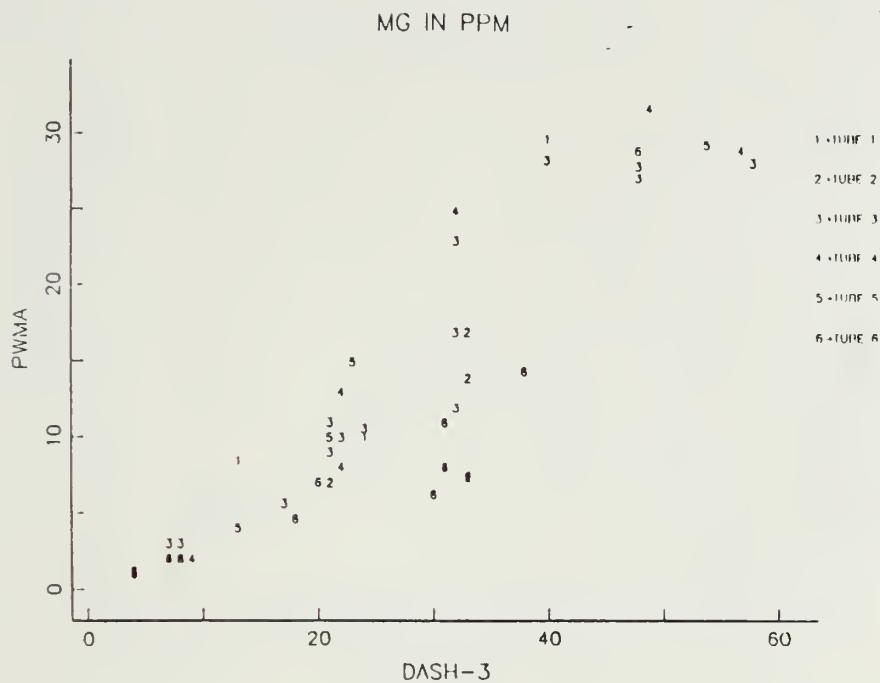


Figure A.24 Graphite Tube Scatterplot-Location:Myrtle Beach-Element:Mg.

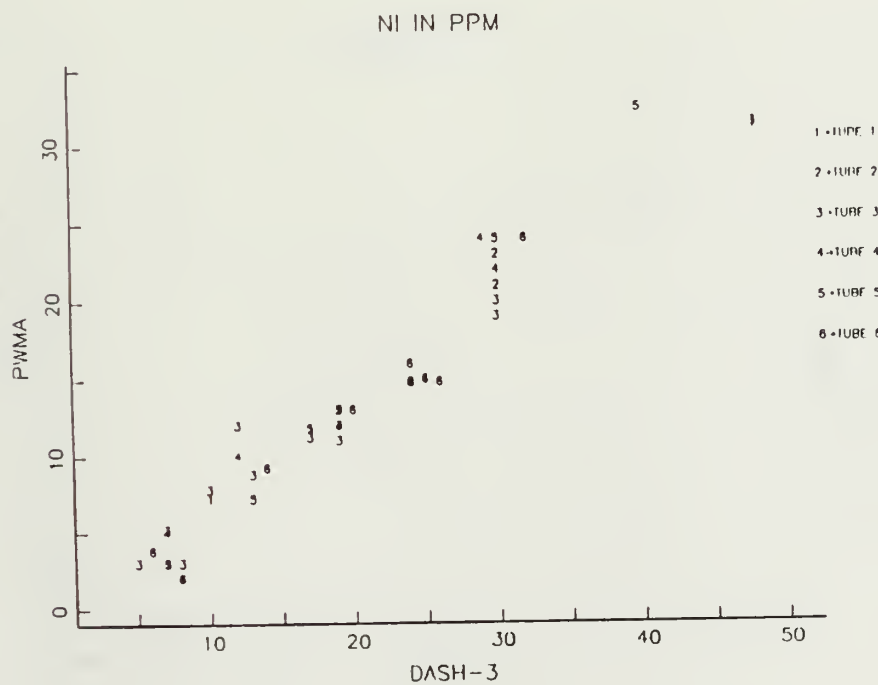


Figure A.25 Graphite Tube Scatterplot-Location:Myrtle Beach-Element:Ni.

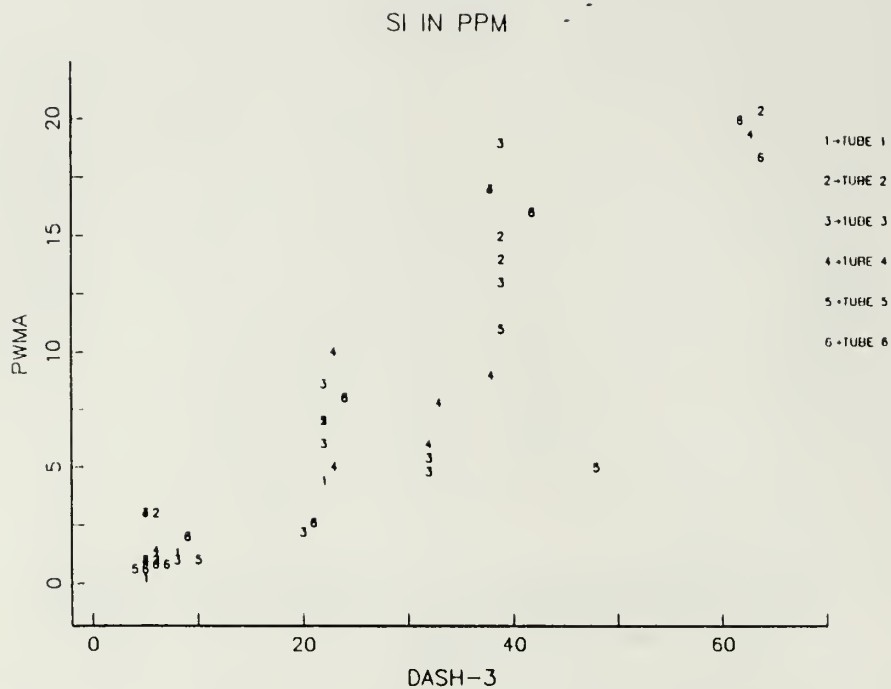


Figure A.26 Graphite Tube Scatterplot-Location:Myrtle Beach-Element:Si.

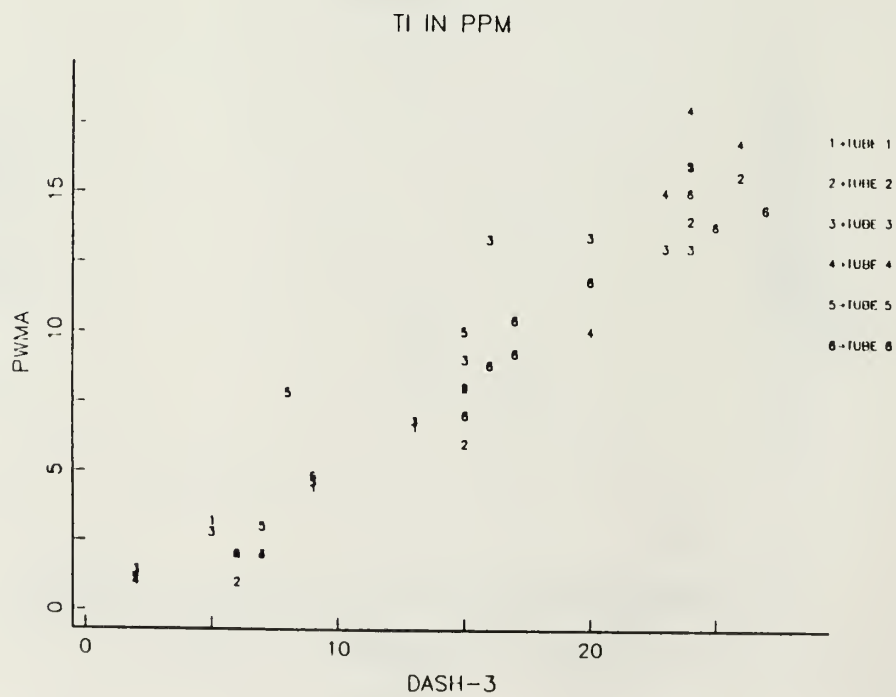


Figure A.27 Graphite Tube Scatterplot-Location:Myrtle Beach-Element:Ti.

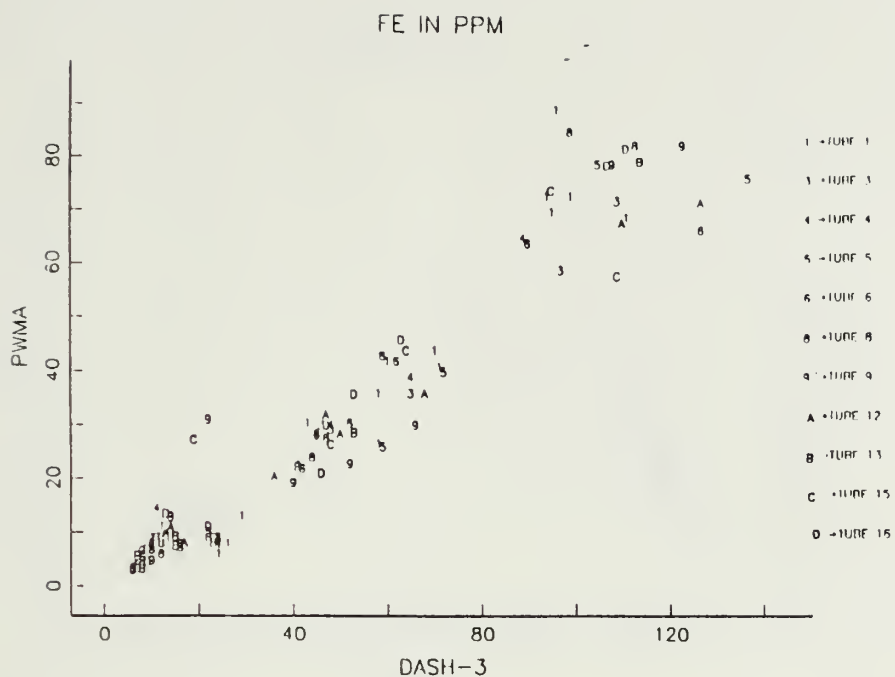


Figure A.28 Graphite Tube Scatterplot-Location:Pensacola-Element:Fe.

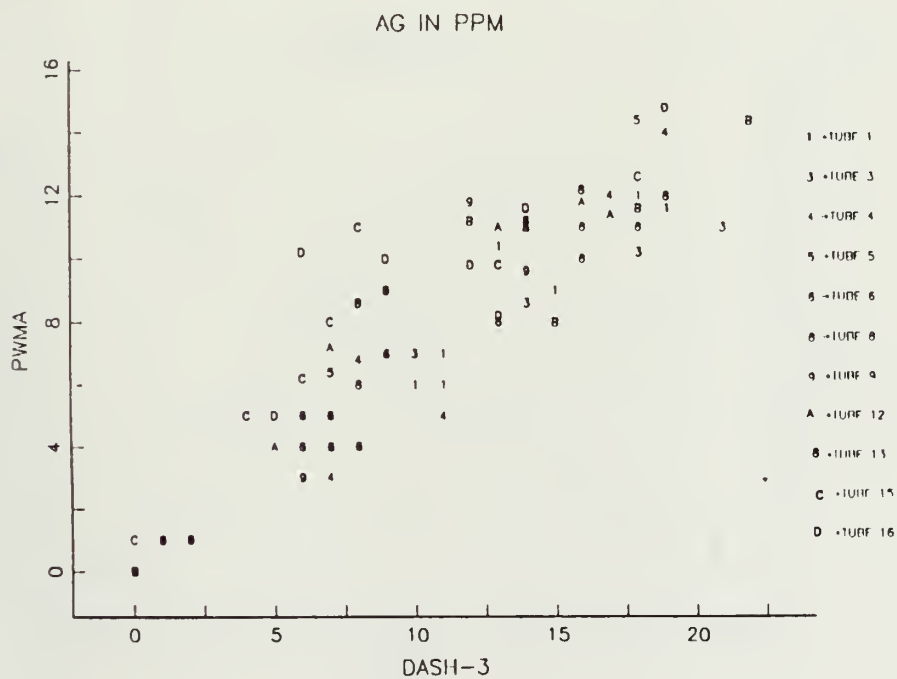


Figure A.29 Graphite Tube Scatterplot-Location:Pensacola-Element:Ag.



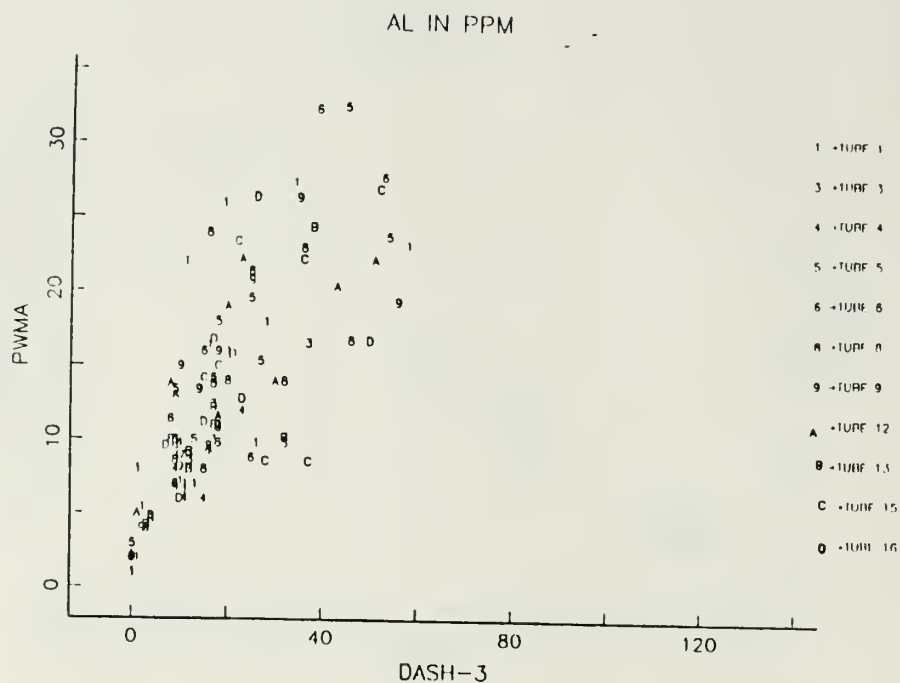


Figure A.30 Graphite Tube Scatterplot-Location:Pensacola-Element:Al.

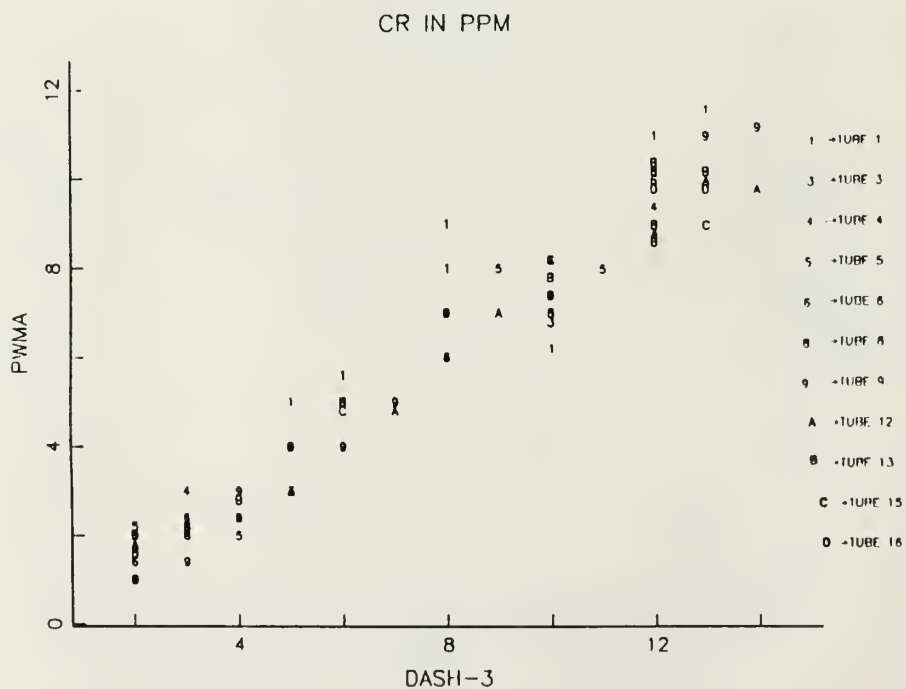


Figure A.31 Graphite Tube Scatterplot-Location:Pensacola-Element:Cr.

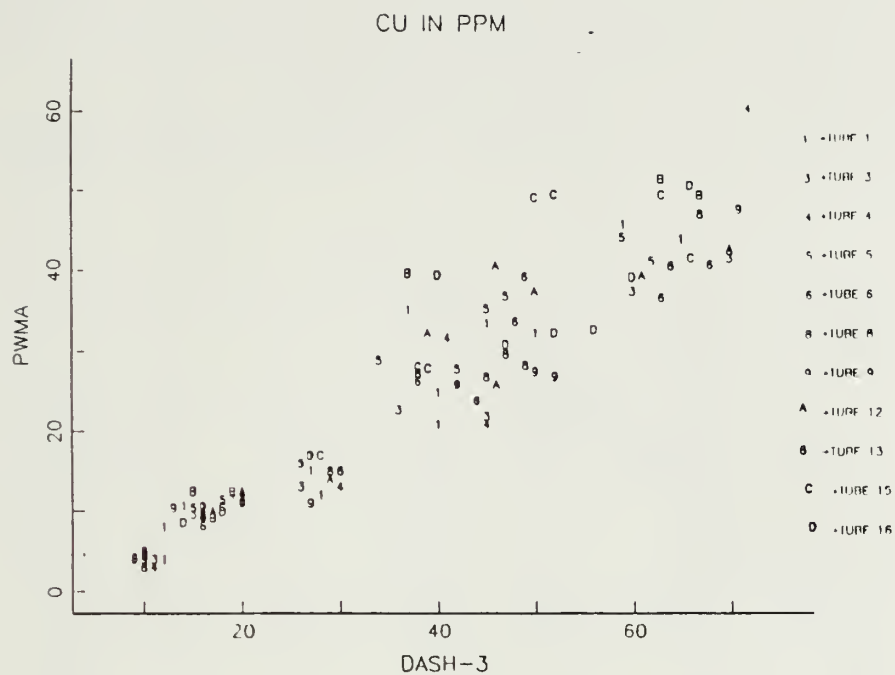


Figure A.32 Graphite Tube Scatterplot-Location:Pensacola-Element:Cu.

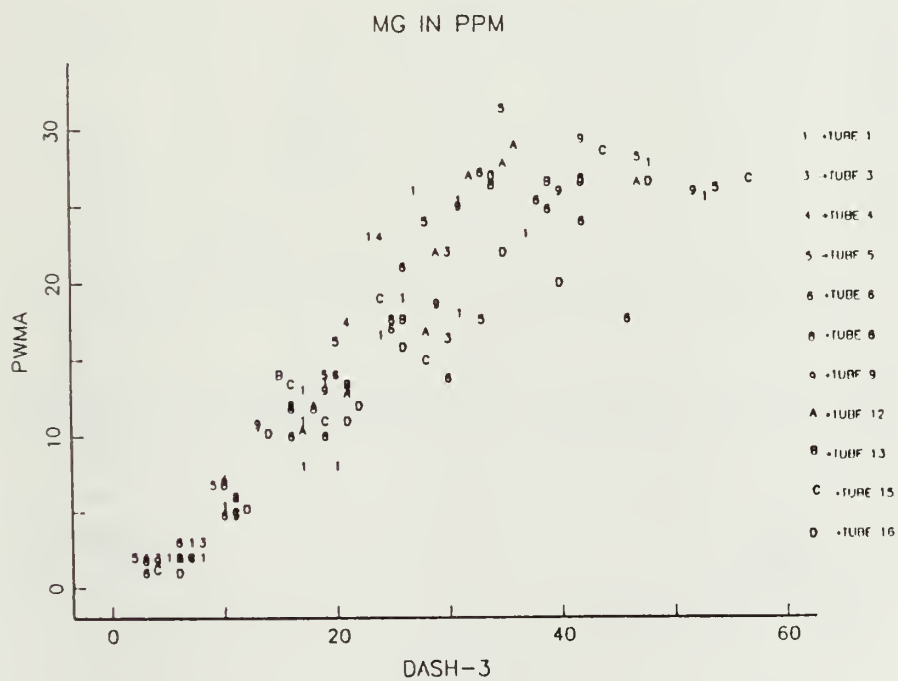


Figure A.33 Graphite Tube Scatterplot-Location:Pensacola-Element:Mg.

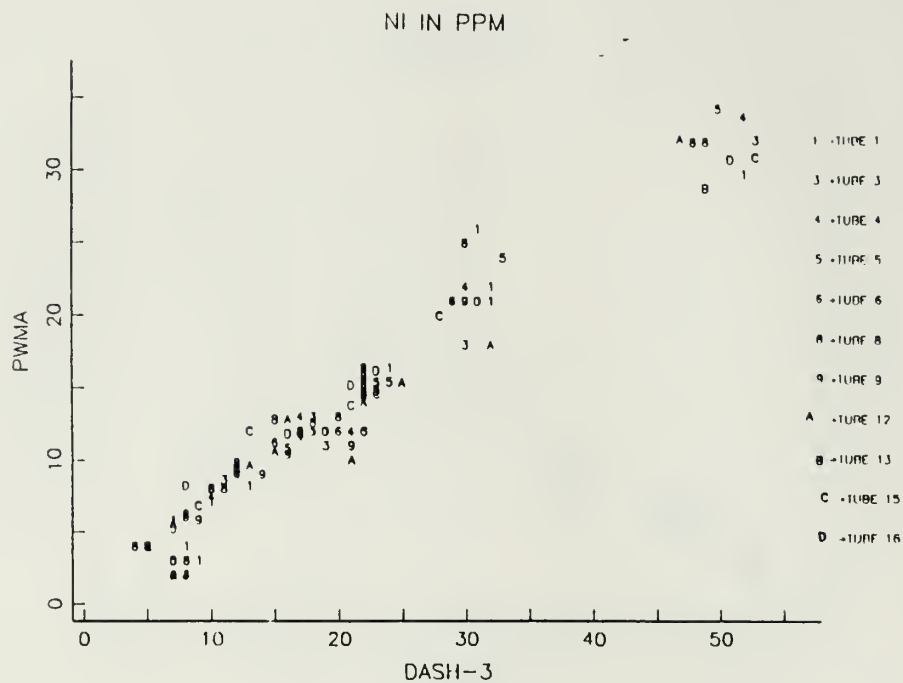


Figure A.34 Graphite Tube Scatterplot-Location:Pensacola-Element:Ni.

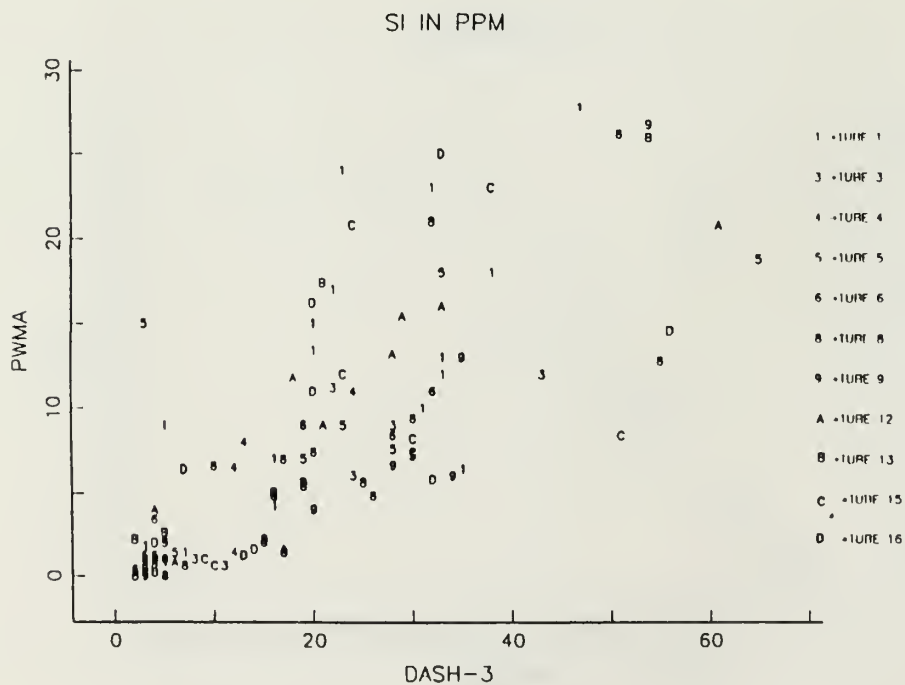


Figure A.35 Graphite Tube Scatterplot-Location:Pensacola-Element:Si.

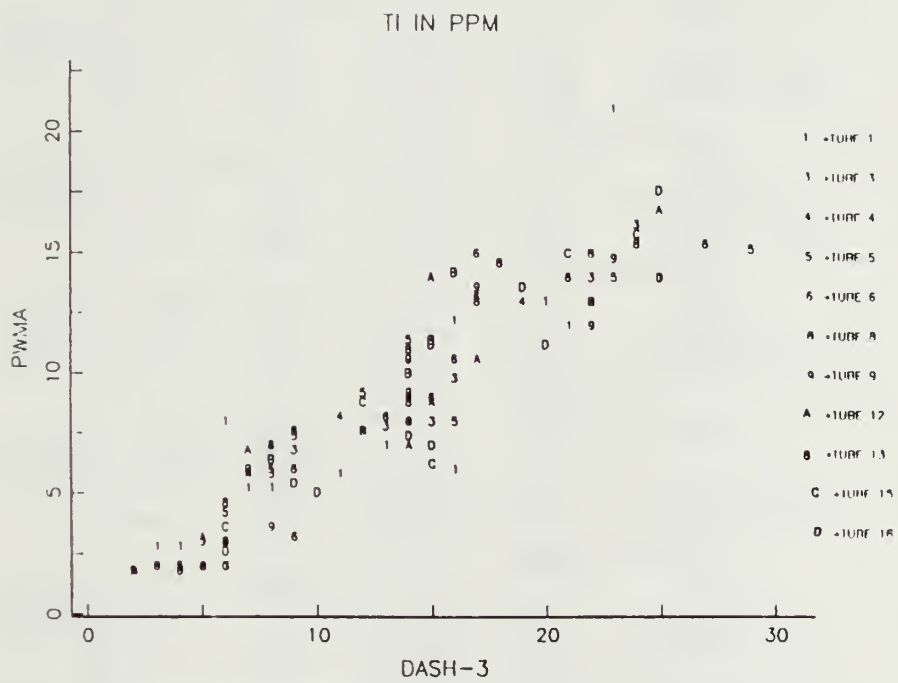


Figure A.36 Graphite Tube Scatterplot-Location:Pensacola-Element:Ti.

# APPENDIX B

## ANOVA TABLES FOR CORRELATION DATA

TABLE 27  
PWMA CORRELATION DATA ANOVA TABLES

PWMA	ELEMENT: FE				
SOURCE	DF	ANOVA SS	MEAN SQ	F VALUE	PR > F
LOC	3	2166.66	722.11	65.83	0.0001
SAM	8	58909.09	7363.63	671.15	0.0001
LOC*SAM	24	1980.91	82.53	7.52	0.0001
ERROR	143	1368.95	10.97		
TOTAL	178	64625.63	R-SQUARE	0.975	
PWMA	ELEMENT: AG				
SOURCE	DF	ANOVA SS	MEAN SQ	F VALUE	PR > F
LOC	3	97.43	32.47	18.45	0.0001
SAM	8	3686.02	460.75	267.36	0.0001
LOC*SAM	24	71.45	2.97	1.73	0.0265
ERROR	144	248.16	1.72		
TOTAL	179	4103.07	R-SQUARE	0.939	
PWMA	ELEMENT: AL				
SOURCE	DF	ANOVA SS	MEAN SQ	F VALUE	PR > F
LOC	3	368.81	122.93	9.63	0.0001
SAM	8	6575.15	821.89	64.36	0.0001
LOC*SAM	23	796.68	34.63	2.71	0.0002
ERROR	146	1864.51	12.77		
TOTAL	180	9605.16	R-SQUARE	0.805	
PWMA	ELEMENT: CR				
SOURCE	DF	ANOVA SS	MEAN SQ	F VALUE	PR > F
LOC	3	140.66	46.88	66.57	0.0001
SAM	8	1900.06	237.50	337.21	0.0001
LOC*SAM	24	54.32	2.26	3.21	0.0001
ERROR	145	102.12	0.70		
TOTAL	180	2197.18	R-SQUARE	0.953	
PWMA	ELEMENT: CU				
SOURCE	DF	ANOVA SS	MEAN SQ	F VALUE	PR > F
LOC	3	2220.14	740.04	29.82	0.0001
SAM	8	34714.56	4339.32	174.84	0.0001
LOC*SAM	24	277.10	11.54	0.47	0.9844
ERROR	144	3573.96	24.81		
TOTAL	179	40785.78	R-SQUARE	0.912	
PWMA	ELEMENT: MG				
SOURCE	DF	ANOVA SS	MEAN SQ	F VALUE	PR > F
LOC	3	374.60	124.86	26.14	0.0001
SAM	8	16900.49	2112.56	442.23	0.0001
LOC*SAM	24	723.43	30.14	6.31	0.0001
ERROR	142	678.34	4.77		
TOTAL	177	18676.88	R-SQUARE	0.963	
PWMA	ELEMENT: NI				
SOURCE	DF	ANOVA SS	MEAN SQ	F VALUE	PR > F
LOC	3	557.60	185.86	79.51	0.0001
SAM	8	10538.85	1317.35	563.55	0.0001
LOC*SAM	24	51.21	2.13	0.91	0.5846
ERROR	146	341.28	2.33		
TOTAL	181	11488.95	R-SQUARE	0.970	
PWMA	ELEMENT: SI				
SOURCE	DF	ANOVA SS	MEAN SQ	F VALUE	PR > F
LOC	3	154.30	51.43	7.00	0.0002
SAM	8	5616.72	702.09	95.54	0.0001
LOC*SAM	24	283.16	11.79	1.61	0.0473
ERROR	143	1050.80	7.34		
TOTAL	178	7104.99	R-SQUARE	0.852	
PWMA	ELEMENT: TI				
SOURCE	DF	ANOVA SS	MEAN SQ	F VALUE	PR > F
LOC	3	186.14	62.04	51.98	0.0001
SAM	8	2875.53	359.44	301.10	0.0001
LOC*SAM	24	118.79	4.94	4.15	0.0001
ERROR	144	171.90	1.19		
TOTAL	179	3352.37	R-SQUARE	0.948	

TABLE 28  
DASH-3 CORRELATION DATA ANOVA TABLES

DASH-3	ELEMENT: FE				
SOURCE	DF	ANOVA SS	MEAN SQ	F VALUE	PR > F
LOC	3	1011.11	337.03	17.25	0.0001
SAM	8	208611.88	26076.48	1334.93	0.0001
LOC*SAM	24	1394.88	58.12	2.98	0.0001
ERROR	145	2832.42	19.53		
TOTAL	180	213850.30	R-SQUARE	0.986	
DASH-3	ELEMENT: AG				
SOURCE	DF	ANOVA SS	MEAN SQ	F VALUE	PR > F
LOC	3	415.53	138.51	63.16	0.0001
SAM	8	11078.53	1384.81	631.43	0.0001
LOC*SAM	24	0.00	0.0	0.00	1.0000
ERROR	147	322.39	2.19		
TOTAL	182	11777.04	R-SQUARE	0.972	
DASH-3	ELEMENT: AL				
SOURCE	DF	ANOVA SS	MEAN SQ	F VALUE	PR > F
LOC	3	1303.70	434.56	45.61	0.0001
SAM	8	32746.02	4093.25	429.58	0.0001
LOC*SAM	23	0.00	0.0	0.00	1.0000
ERROR	147	1400.68	9.52		
TOTAL	181	34753.14	R-SQUARE	0.959	
DASH-3	ELEMENT: CR				
SOURCE	DF	ANOVA SS	MEAN SQ	F VALUE	PR > F
LOC	3	85.48	28.49	73.01	0.0001
SAM	8	3730.40	466.30	1194.68	0.0001
LOC*SAM	24	0.00	0.0	0.00	1.0000
ERROR	147	57.37	0.39		
TOTAL	182	3816.10	R-SQUARE	0.984	
DASH-3	ELEMENT: CU				
SOURCE	DF	ANOVA SS	MEAN SQ	F VALUE	PR > F
LOC	3	546.24	182.08	13.02	0.0001
SAM	8	76723.17	9590.39	685.78	0.0001
LOC*SAM	24	612.88	25.53	1.83	0.0163
ERROR	145	2027.76	13.98		
TOTAL	180	79910.06	R-SQUARE	0.974	
DASH-3	ELEMENT: MG				
SOURCE	DF	ANOVA SS	MEAN SQ	F VALUE	PR > F
LOC	3	1006.78	335.59	39.65	0.0001
SAM	8	42531.79	5316.47	628.18	0.0001
LOC*SAM	22	273.61	12.43	1.47	0.0935
ERROR	144	1218.71	8.46		
TOTAL	177	45030.90	R-SQUARE	0.972	
DASH-3	ELEMENT: NI				
SOURCE	DF	ANOVA SS	MEAN SQ	F VALUE	PR > F
LOC	3	13.38	4.46	1.19	0.3151
SAM	8	32406.82	4050.85	1061.77	0.0001
LOC*SAM	24	240.12	10.00	2.67	0.0002
ERROR	146	546.72	3.74		
TOTAL	181	33207.05	R-SQUARE	0.983	
DASH-3	ELEMENT: SI				
SOURCE	DF	ANOVA SS	MEAN SQ	F VALUE	PR > F
LOC	3	985.45	328.48	29.05	0.0001
SAM	8	51603.95	6540.49	570.40	0.0001
LOC*SAM	24	0.00	0.00	0.00	1.0000
ERROR	145	1639.75	11.30		
TOTAL	180	54103.80	R-SQUARE	0.969	
DASH-3	ELEMENT: TI				
SOURCE	DF	ANOVA SS	MEAN SQ	F VALUE	PR > F
LOC	3	110.31	36.77	14.72	0.0001
SAM	8	7895.61	986.95	395.05	0.0001
LOC*SAM	24	116.12	4.83	1.94	0.0093
ERROR	144	359.75	2.49		
TOTAL	179	8481.80			



# APPENDIX C

## ANOVA TABLES FOR VERIFICATION DATA

TABLE 29  
PWMA VERIFICATION DATA ANOVA TABLES

PWMA ELEMENT: FE					
SOURCE	DF	ANOVA SS	MEAN SQ	F VALUE	PR > F
LOC	3	869.83	289.94	5.20	0.0021
LEV	2	86677.45	43338.72	777.30	0.0001
LOC*LEV	6	339.91	56.65	1.02	0.4171
ERROR	150	8363.29	55.75		
TOTAL	161	96250.50	R-SQUARE	0.913	
PWMA ELEMENT: AG					
SOURCE	DF	ANOVA SS	MEAN SQ	F VALUE	PR > F
LOC	3	10.12	3.37	3.64	0.0143
LEV	2	1153.04	576.52	621.30	0.0001
LOC*LEV	6	7.02	1.17	1.26	0.2787
ERROR	152	141.04	0.92		
TOTAL	163	1311.23	R-SQUARE	0.892	
PWMA ELEMENT: AL					
SOURCE	DF	ANOVA SS	MEAN SQ	F VALUE	PR > F
LOC	3	289.79	96.59	6.91	0.0003
LEV	2	4884.17	2442.08	174.66	0.0001
LOC*LEV	6	161.23	26.87	1.92	0.0809
ERROR	148	2069.38	13.98		
TOTAL	159	7404.59	R-SQUARE	0.720	
PWMA ELEMENT: CR					
SOURCE	DF	ANOVA SS	MEAN SQ	F VALUE	PR > F
LOC	3	11.60	3.86	5.96	0.0008
LEV	2	950.84	475.42	733.27	0.0001
LOC*LEV	6	4.04	0.67	1.04	0.4011
ERROR	152	98.55	0.64		
TOTAL	163	1065.04	R-SQUARE	0.907	
PWMA ELEMENT: CU					
SOURCE	DF	ANOVA SS	MEAN SQ	F VALUE	PR > F
LOC	3	13.62	4.54	0.41	0.7460
LEV	2	12199.09	6099.54	557.39	0.0001
LOC*LEV	6	0.00	0.00	0.00	1.0000
ERROR	151	1652.41	10.94		
TOTAL	162	13860.60	R-SQUARE	0.881	
PWMA ELEMENT: MG					
SOURCE	DF	ANOVA SS	MEAN SQ	F VALUE	PR > F
LOC	3	771.97	257.33	44.53	0.0001
LEV	2	5657.29	2828.64	489.55	0.0001
LOC*LEV	6	553.27	92.21	15.96	0.0001
ERROR	151	872.48	5.77		
TOTAL	162	7855.01	R-SQUARE	0.889	
PWMA ELEMENT: NI					
SOURCE	DF	ANOVA SS	MEAN SQ	F VALUE	PR > F
LOC	3	34.76	11.58	3.02	0.0311
LEV	2	9225.36	4612.68	1203.89	0.0001
LOC*LEV	6	16.04	2.67	0.70	0.6516
ERROR	152	582.38	3.83		
TOTAL	163	9858.56	R-SQUARE	0.941	
PWMA ELEMENT: SI					
SOURCE	DF	ANOVA SS	MEAN SQ	F VALUE	PR > F
LOC	3	144.83	48.27	2.20	0.0894
LEV	2	6687.15	3343.57	152.16	0.0001
LOC*LEV	6	130.66	21.77	0.99	0.4335
ERROR	148	3252.08	21.97		
TOTAL	159	10214.74	R-SQUARE	0.681	
PWMA ELEMENT: TI					
SOURCE	DF	ANOVA SS	MEAN SQ	F VALUE	PR > F
LOC	3	8.17	2.72	0.96	0.4144
LEV	2	4170.26	2085.13	735.55	0.0001
LOC*LEV	6	15.93	2.65	0.94	0.4706
ERROR	151	428.05	2.83		
TOTAL	162	4622.41	R-SQUARE	0.907	

TABLE 30  
DASH-3 VERIFICATION DATA ANOVA TABLES

DASH-3	ELEMENT: FE					
SOURCE	DF	ANOVA SS	MEAN SQ	F VALUE	PR > F	
LOC	3	254.58	84.86	2.88	0.0376	
LEV	2	172498.44	86248.22	2922.57	0.0001	
LOC*LEV	6	680.95	113.49	3.85	0.0013	
ERROR	150	4426.71	29.51			
TOTAL	161	177860.69	R-SQUARE	0.975		
DASH-3	ELEMENT: AG					
SOURCE	DF	ANOVA SS	MEAN SQ	F VALUE	PR > F	
LOC	3	96.23	32.07	55.93	0.0001	
LEV	2	2202.02	1101.01	1919.82	0.0001	
LOC*LEV	6	24.95	4.15	7.25	0.0001	
ERROR	152	37.17	0.57			
TOTAL	163	2410.39	R-SQUARE	0.964		
DASH-3	ELEMENT: AL					
SOURCE	DF	ANOVA SS	MEAN SQ	F VALUE	PR > F	
LOC	3	264.38	88.12	38.36	0.0001	
LEV	2	9322.24	4661.12	2028.82	0.0001	
LOC*LEV	6	59.32	9.85	4.30	0.0005	
ERROR	148	340.02	2.29			
TOTAL	159	9985.97	R-SQUARE	0.966		
DASH-3	ELEMENT: CR					
SOURCE	DF	ANOVA SS	MEAN SQ	F VALUE	PR > F	
LOC	3	14.89	4.96	27.36	0.0001	
LEV	2	1248.38	624.19	3438.30	0.0001	
LOC*LEV	6	4.64	0.77	4.27	0.0005	
ERROR	152	27.59	0.18			
TOTAL	163	1295.53	R-SQUARE	0.979		
DASH-3	ELEMENT: CU					
SOURCE	DF	ANOVA SS	MEAN SQ	F VALUE	PR > F	
LOC	3	119.39	39.79	8.64	0.0001	
LEV	2	29005.61	14502.80	3147.48	0.0001	
LOC*LEV	6	77.88	12.98	2.82	0.0126	
ERROR	151	695.77	4.60			
TOTAL	162	29898.66	R-SQUARE	0.977		
DASH-3	ELEMENT: MG					
SOURCE	DF	ANOVA SS	MEAN SQ	F VALUE	PR > F	
LOC	3	386.94	128.98	34.46	0.0001	
LEV	2	14792.03	7396.01	1975.99	0.0001	
LOC*LEV	6	76.43	12.73	3.40	0.0035	
ERROR	151	565.18	3.74			
TOTAL	162	15820.60	R-SQUARE	0.964		
DASH-3	ELEMENT: NI					
SOURCE	DF	ANOVA SS	MEAN SQ	F VALUE	PR > F	
LOC	3	12.04	4.01	2.02	0.1120	
LEV	2	14923.88	7461.94	3752.34	0.0001	
LOC*LEV	6	22.70	3.78	1.90	0.0838	
ERROR	152	302.26	1.98			
TOTAL	163	15260.90	R-SQUARE	0.980		
DASH-3	ELEMENT: SI					
SOURCE	DF	ANOVA SS	MEAN SQ	F VALUE	PR > F	
LOC	3	285.48	95.16	10.28	0.0001	
LEV	2	25559.84	12779.92	1380.22	0.0001	
LOC*LEV	6	228.78	38.13	4.12	0.0007	
ERROR	148	1370.37	9.25			
TOTAL	159	27444.49	R-SQUARE	0.950		
DASH-3	ELEMENT: TI					
SOURCE	DF	ANOVA SS	MEAN SQ	F VALUE	PR > F	
LOC	3	98.08	32.69	13.81	0.0001	
LEV	2	8596.55	4298.27	1816.22	0.0001	
LOC*LEV	6	36.29	6.04	2.56	0.0219	
ERROR	151	357.35	2.36			
TOTAL	162	9088.29	R-SQUARE	0.961		

## APPENDIX D

### REGRESSION MODEL

The primary regression model used in this paper was the simple linear regression model with least squares estimators. The equation yielded from this model will give the best linear unbiased estimates for the data when all assumptions are met. The general straight line regression model is given in Equation D.1 .

$$y_i = a + bx_i + e_i . \quad (\text{eqn D.1})$$

The assumptions used for this model are [Ref. 11: p. 465]:

- 1) *We have a population of y values for each  $x_i$ ; the population variable corresponding to  $x_i$  is  $y_i$  .*
- 2)  *$E[Y_i] = a + bx_i$  for each  $x_i$  ( $E[e_i] = 0$ ).*
- 3)  *$Var[Y_i] = \sigma^2$  for each  $x_i$  (homoscedascity).*
- 4) *The errors of observation,  $e_i = y_i - a - bx_i$  are uncorrelated.*

Solutions to the regression model are obtained through least squares estimation techniques. The resultant equations that provide the estimates are:

$$\hat{b} = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sum(x_i - \bar{x})^2} , \quad (\text{eqn D.2})$$

$$\hat{a} = \bar{y} - \hat{b}\bar{x} , \quad (\text{eqn D.3})$$

where

$$\bar{y} = (\sum y_i)/n , \quad (\text{eqn D.4})$$

and

$$\bar{x} = (\sum x_i)/n . \quad (\text{eqn D.5})$$

The variance estimates are:

$$\hat{s}_b^2 = \frac{s^2}{\sum (x_i - \bar{x})^2} \quad . \quad \quad \quad \text{(eqn D.6)}$$

and

$$\hat{s}_a^2 = \frac{s^2 \sum x_i^2}{\sum (x_i - \bar{x})^2} \quad . \quad \quad \quad \text{(eqn D.7)}$$

where

$$s^2 = (n-2)^{-1} \sum (y_i - \hat{a} - \hat{b}x_i)^2 \quad . \quad \quad \quad \text{(eqn D.8)}$$

## LIST OF REFERENCES

1. Commander, Naval Air Systems Command, *Joint Oil Analysis Program Laboratory Manual (NAVAIR 17-15-50)*, Naval Air Systems Command, Washington, D.C., March 1978.
2. Menard, Thomas A., *Aircraft Engine Oil Analysis by Neutron Activation Techniques*, FJSRL-TR-78-0016, Frank J. Seiler Research Laboratory, USAFA, CO, December 1978.
3. Senholzi, P.B., *Oil Analysis*, NAEC-92-153, Naval Air Engineering Center, Lakehurst, NJ, August 1982.
4. Niu, William, *Final Technical Report-Portable Wear Metal Analyzer*, AFWAL-TR-85-2403 Air Force Wright Aeronautical Laboratories, Wright-Patterson AFB, OH, August 1985.
5. Rhine, W.E., and Kauffman, R.E., *Sample Introduction Methods for Improving the Particle Detection Capability of the Spectrometric Oil Analysis Program*, NAEC-92-185, Naval Air Engineering Center, Lakehurst, NJ, January 1985.
6. Rhine, W.E., Saba, C.S., and Kauffman, R.E., *Spectrometer Sensitivity Investigations on the Spectrometric Oil Analysis Program*, NAEC-92-169, Naval Air Engineering Center, Lakehurst, NJ, April 1983.
7. Rippen, M.E., O'Haver T., and Gibert T., *Laboratory Spectrometer for Wearmetal Analysis of Engine Lubricants*, AFWAL-TR-85-2101 Air Force Wright Aeronautical Laboratories, Wright-Patterson AFB, OH, April 1986.
8. Perkin-Elmer Corporation, *Operating and Maintenance Instrutions Portable Wear Metal Analyzer*, Perkin-Elmer Corporation, Pomona, CA, March 1985.
9. Jayachandran, T., and Larson, H.J., *PWMA Field Test*, NPS-53-86-0002PR, Naval Postgraduate School, CA, January 1986.
10. Air Force Wright Aeronautical Laboratories, *Field Test Plan for Evaluation of the Portable Wear Metal Analyzer*, Wright-Patterson AFB, OH, April 1985.
11. Larson, Harold J., *Introduction to Probability Theory and Statistical Inference, 3rd Edition*, John Wiley and Sons, New York, NY, 1982.

12. Neter, J., Wasserman, W., and Kutner, M.H., *Applied Linear Statistical Models*, 2nd Edition, Irwin, Homewood, Ill, 1985.



# INITIAL DISTRIBUTION LIST

	No. Copies
1. Defense Technical Information Center Cameron Station Alexandria, VA 22304-6145	2
2. Library, Code 0142 Naval Postgraduate School Monterey, CA 93943-5002	2
3. Professor H. J. Larson (Code 55La) Department of Operations Research Naval Postgraduate School Monterey, California	6
4. Lieutenant James T. Stewart SWOS DHS Class 101 NETC Newport, Rhode Island 02840	1
5. Professor R. R. Read (Code 55Re) Department of Operations Research Naval Postgraduate School Monterey, California	2





LIBRARY  
SCHOOL  
03-17-6002

T  
S Thesis  
c S71453 Stewart  
c.1 A comparison of mea-  
surements from the A/E35U-  
3 and PWMA spectrometers.

23 AUG 90

36209

Thesis  
S71453 Stewart  
c.1 A comparison of mea-  
surements from the A/E35U-  
3 and PWMA spectrometers.

thesS71453

A comparison of measurements from the A/



3 2768 000 75425 3

DUDLEY KNOX LIBRARY